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Population dynamics of Northwest Atlantic porbeagle (*Lamna nasus*), with an assessment of status and projections for recovery

Dynamique des populations de la maraîche de l'Atlantique Nord-Ouest (*Lamna nasus*), avec une évaluation de la situation et des prévisions de rétablissement

S.E. Campana, A.J.F. Gibson, M. Fowler, A. Dorey, and W. Joyce

Population Ecology Division
Science Branch, Maritimes Region
Department of Fisheries and Oceans
Bedford Institute of Oceanography
P.O. Box 1006, 1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2

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ABSTRACT

As part of the International Commission for the Conservation of Atlantic Tunas (ICCAT) Shark Stock Assessment Meeting in Copenhagen, Denmark, in 2009, a stock assessment for Northwest Atlantic porbeagle shark (*Lamna nasus*) was prepared. A forward projecting, age- and sex-structured life history model was used, which was fit to catch-at-length and catch per unit effort data to the end of 2008, to evaluate porbeagle population dynamics. The assessment was also intended to assess the expected time frames for recovery under different management scenarios. This assessment was tabled at Fisheries and Oceans Canada's 2012 pre-COSEWIC (Committee on the Status of Endangered Wildlife in Canada) review of porbeagle shark, although catch, discards and certain research results have been updated to the end of 2011.

Four variants of the population model are presented, all of which differ in their assumed productivity. The total population size is currently estimated to be about 22% to 27% of its size in 1961 and about 95% to 103% its size in 2001. The estimated number of mature females in 2009 is in the range of 11,000 to 14,000 individuals, or 12% to 16% of its 1961 level and 83% to 103% of its 2001 value.

All analyses indicate that this porbeagle population can recover at modest fishing mortalities, but that the time horizon for recovery is sensitive to the amount of human-induced mortality. All population models predict recovery to 20% of spawning stock numbers ($SSN_{20\%}$) before 2014 if the human-induced mortality rate is kept at or below 4% of the vulnerable biomass. The model with the lowest assumed productivity predicts that recovery will occur if human-induced mortality is less than 4% the vulnerable biomass, but not at 8%. All other models predict recovery under higher exploitation rates. Under the low productivity model, recovery to spawning stock numbers at maximum sustainable yield (SSN_{MSY}) is predicted to take over 100 years at exploitation rates of 4% of the vulnerable biomass. These estimates are conditional on the assumed selectivity. Assuming the Shelf-Edge selectivity, Models 1, 3 and 4 (all of which fit better than low-productivity Model 2) predict that keeping the rate of human-induced mortality to less than 4% of the vulnerable biomass would be precautionary and would keep expected recovery times to SSN_{MSY} on the order of decades.

RÉSUMÉ

Dans le cadre de la réunion d'évaluation du stock de requins de la Commission internationale pour la conservation des thonidés de l'Atlantique (CICTA), qui s'est déroulée en 2009 à Copenhague, au Danemark, une évaluation du stock de la maraîche de l'Atlantique Nord-Ouest (*Lamna nasus*) a été préparée. On a utilisé un modèle de projection prospective du cycle biologique structuré selon l'âge et le sexe, qui utilisait les données sur les captures selon la longueur et les captures par unité d'effort jusqu'à la fin de 2008, de façon à évaluer la dynamique de la population de maraîche. L'évaluation visait également à déterminer le temps prévu du rétablissement selon différents scénarios de gestion. Elle a été présentée dans le cadre de l'examen de la maraîche réalisé en 2012 par Pêches et Océans Canada, qui précédait celui du COSEPAC (Comité sur la situation des espèces en péril au Canada). Toutefois, les résultats concernant les prises, les rejets et certaines recherches ont été mis à jour à la fin de 2011.

Quatre variations du modèle de population sont présentées, et chacune d'entre elles diffère quant à leur productivité hypothétique. On estime que la taille actuelle de la population se situe entre 22 % et 27 % par rapport à sa taille de 1961, et entre 95 % et 103 % de sa taille de 2001. Le nombre estimé de femelles matures en 2009 varierait de 11 000 à 14 000 individus, c'est-à-dire de 12 % à 16 % de son niveau de 1961, et de 83 % à 103 % de son niveau de 2001.

Toutes les analyses indiquent que cette population de maraîche peut se rétablir selon un faible taux de mortalité par pêche, mais que l'horizon temporel du rétablissement dépend du taux de mortalité anthropique. Tous les modèles de population prévoient un rétablissement qui atteindrait 20 % de l'effectif du stock reproducteur ($ESR_{20\,\%}$) avant 2014 si le taux de mortalité anthropique était maintenu à 4 % ou moins de la biomasse vulnérable. Le modèle de productivité hypothétique la plus faible prévoit un rétablissement si le taux de mortalité anthropique est inférieur à 4 % de la biomasse vulnérable, mais pas à 8 %. Tous les autres modèles prévoient un rétablissement à des taux d'exploitation plus élevés. Selon le modèle de productivité faible, un rétablissement atteignant l'effectif du stock reproducteur, selon la production maximale soutenable (ESR_{PMS}), devrait prendre plus de 100 ans à des taux d'exploitation de 4 % de la biomasse vulnérable. Ces estimations dépendent de la sélectivité hypothétique. En supposant une sélectivité sur le bord du plateau, les modèles 1, 3 et 4 (qui représentent une meilleure option que le modèle 2 de productivité faible) prévoient qu'il serait prudent de maintenir le taux de mortalité anthropique à moins de 4 % de la biomasse vulnérable et que le temps de rétablissement de l'effectif du stock reproducteur, selon la production maximale soutenable, serait ainsi de l'ordre de décennies.

INTRODUCTION

The porbeagle shark (*Lamna nasus*) is a large cold-temperate pelagic shark species of the family Lamnidae that occurs in the North Atlantic, South Atlantic and South Pacific oceans. The species range extends from Newfoundland (NF) to New Jersey and possibly to South Carolina in the west Atlantic, and from Iceland and the western Barents Sea to Morocco and the Mediterranean in the east Atlantic. It is the only large shark species for which a directed commercial fishery exists in Canadian coastal waters.

Fisheries management plans for pelagic sharks in Atlantic Canada established non-restrictive catch guidelines of 1500 t for porbeagle prior to 1997 (O'Boyle et al. 1996). Because of the limited scientific information that was available at the time, abundance, mortality and yield calculations could not be made. Therefore, a provisional total allowable catch (TAC) of 1000 t was set in place for the period 1997-1999, based largely on historic catches and the observation that recent catch rates had declined (O'Boyle et al. 1998).

In 1998, an intensive research program on all aspects of porbeagle biology and population dynamics was initiated at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia. The research was carried out with the support and funding of the porbeagle shark fishing industry, and in collaboration with the Apex Predators Program of the U.S. National Marine Fisheries Service (NMFS), and greatly increased our understanding of porbeagle biology and population dynamics (Campana et al. 2002a,b, 2003, 2008; Campana and Joyce 2004; Cassoff et al. 2007; Jensen et al. 2002; Joyce et al. 2002; Natanson et al. 2002). The research program led to two analytical stock assessments of porbeagle (Campana et al. 1999, 2001). Based on those assessments, the Shark Management Plan for 2002-2006 reduced the TAC to 250 t, a value that was thought to correspond with F_{msy} and was expected to allow for stock recovery. An updated assessment in 2005 (Gibson and Campana 2005) further reduced the TAC to 185t, with 125t allocated to the directed fishery in Scotia-Fundy, 50 t for bycatch, and 10 t to the Gulf of St. Lawrence.

In May 2004, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) designated the porbeagle as an endangered species, and recommended that it be listed under Schedule 1 of Canada's *Species at Risk Act* (SARA) (COSEWIC 2004). After extensive consultations both within and outside of government, the decision was taken not to list the species under SARA. The basis for the decision was that the porbeagle population was lower than desirable (standing at about 190,000 sharks in 2005), but was projected to be increasing, and that catch levels for the fishery were intentionally set at levels which would allow the population to recover. Implicit in this decision was the recognition that if population recovery could not be demonstrated, the desirability of the fishery would be re-evaluated.

The present document provides a summary of current population status and recovery potential for porbeagle shark up until 2009, as presented to the International Commission for the Conservation of Atlantic Tunas (ICCAT) Shark Stock Assessment Meeting in Copenhagen, Denmark, in 2009. Landings and catch data, as well as some research results, have since been updated to 2011. The basis for the document is a statistical analysis of available data to the end of 2008 using a life history based, age-structured population model, which is used to evaluate current population status and trends. The population model is then used to evaluate potential recovery trajectories given various management options and exploitation rates, as well as time frames for recovery.

POPULATION BIOLOGY

MORPHOMETRY

Various measures of porbeagle size have been used in the past: Aasen (1963) used dorsal length and a non-standard measure of total length, the Scotia-Fundy Observer Program (SFOP) uses total length (TL), the NF Observer Program (NFOP) uses fork length (FL), dockside monitors have sometimes used dressed carcass weight (DW), and the fishing industry uses inter-dorsal length. To convert all of these measurements into a common currency, it was necessary to develop a series of inter-conversion factors (Campana et al. 1999, 2001). Fork length measured over the curve of the body is the measurement used in this assessment. The most common conversions are shown below.

$FL = 3.64 + 0.95*AasenTL$
$FL_{curved} = FL_{straight}$
$FL = 0.99 + 0.885*TL$
$TL = 1.12*FL$
$W = 0.00005*FL^{2.713}$

where FL is fork length measured over the curve of the body in cm, TL is total length, AasenTL is Aasen's (1963) non-standard measure of TL, and W is live weight in kg.

STOCK STRUCTURE

Evidence presented in previous reports indicates that there is only one stock of porbeagle in the northwest (NW) Atlantic, and that there is no appreciable mixing of porbeagle from the northeast (NE) Atlantic with those in the NW Atlantic (Campana et al. 1999, 2001). Month to month shifts in the location of the fishery suggest that porbeagle carry out extensive annual migrations up and down the east coast of Canada, with no indication of the presence of separate stocks. Porbeagle first appear in the Gulf of Maine, Georges Bank and southern Scotian Shelf in January-February, move northeast along the Scotian Shelf through the spring, and then appear off the south coast of NF and in the Gulf of St. Lawrence in the summer and fall. Catches in the late fall suggest a return movement to the southwest. This pattern is reproduceable from year to year. A map of geographic locations and fishing banks is shown in Figure 1.

The results of tagging studies carried out by Norway, Canada and the U.S. also document extensive annual migrations in the NW Atlantic. A total of 197 recaptures were reported in Campana et al. (1999). A further 12 recaptures have since been reported; all recaptures have been mapped in Figure 2. Movements between the Grand Banks, Scotian Shelf and Gulf of Maine were common. None of the tagged porbeagle were recaptured on the east side of the Atlantic, and none of the porbeagle tagged in the eastern Atlantic were recaptured off the North American coast (Stevens 1990).

Recent research conducted using archival satellite pop-up tags demonstrates that most porbeagle remain within the Canadian and American Exclusive Economic Zone (EEZ), although there is significant movement by some individuals into the high seas (Campana et al. 2010). All mature females whose tags popped off in the spring were found in the Sargasso Sea between Cuba and Bermuda, indicating that the Sargasso Sea is a major pupping ground for the population.

AGE, GROWTH, LONGEVITY AND NATURAL MORTALITY

Porbeagle age can be accurately determined from vertebral sections. The life span of porbeagle is estimated to be between 25 and 46 years and generation time is about 18 years (Campana et al. 2002a; Natanson et al. 2002). In both sexes, growth rate appears to decrease slightly at the onset of sexual maturity. Since females mature at an older age than do males, females grow to a larger size. Figure 3 presents the von Bertalanffy growth parameters by sex, as well as that of the combined sexes. Predicted lengths and weights at each age are also shown, although observed sizes at age 0 and 1 were used to minimize distortions due to seasonality and partial recruitment of the young fish to the fishery.

It is possible that the ages of very old porbeagle (>25 years) are underestimated by vertebral band counts, as has been observed in the slow-growing New Zealand population (Francis et al. 2007). If true, the growth rate of old porbeagle is somewhat slower than that suggested by the von Bertalanffy growth parameters. The fact that the L_{inf} of the females is considerably larger than the largest porbeagles normally observed suggests that growth overestimation of the oldest fish (and only the oldest fish) is a possibility. For this reason, the combined growth curve has been used in most analyses.

Porbeagle are thought to have a low natural mortality. Instantaneous natural mortality is estimated to be 0.10 for immature porbeagle, 0.15 for mature males, and 0.20 for mature females (Campana et al. 2008). Although these estimates are conditional on the gear selectivity assumed in their calculation, they are presently the best available for this population.

PORBEAGLE REPRODUCTION

Porbeagle sharks have low fecundity and a late age of sexual maturation. Jensen et al. (2002) reported that males mature between 160 - 190 cm in FL (L_{50} equals approximately 174 cm; A_{50} approximately Age 8), while females mature between 205 - 230 cm (L_{50} approximately 217 cm; A_{50} approximately Age 13) (Figure 4). Porbeagles are ovoviviparous and oophagous, with an average litter size of 3.9 pups in the NW Atlantic.

Our research indicates that mating occurs in at least two locations. The first mating ground to be identified was on the Grand Banks, off southern NF and at the entrance to the Gulf of St. Lawrence (Figure 5). Most large females collected in these areas in the late summer or early fall were pregnant, suggesting that mating took place during the summer (Jensen et al. 2002). A second mating ground was identified on Georges Bank in June 2007, based on very high catch rates of mature females which did not appear to be feeding (Figure 5). Mature males were absent at the time, suggesting that mating had not yet begun. Allowing for the delay between mating and the production of visible embryos, mating time on Georges Bank and off NF is probably very similar. The location of the pupping ground remains unknown. Birth apparently occurs in late winter or spring after an 8-9 month gestation period (Aasen 1963; Francis and Stevens 2000 Jensen et al. 2002). There is no evidence of an extended latency period after birth, since virtually all sexually mature females are pregnant in the fall. Therefore, the reproductive cycle is 1 year.

TEMPERATURE, DEPTH AND FEEDING

Porbeagle appear to occupy well defined and relatively constant temperatures throughout the year (Campana and Joyce 2004). Based on temperature at the depth of the gear, porbeagle were caught at a mean temperature of 7.4°C, with 50% being caught between 5-10°C. Temperature at depth was a significant predictor of catch rate; however, sea surface

temperature was a poor predictor of catch rate. There was no significant seasonal pattern in temperature, suggesting that the porbeagle adjusted their location to occupy the preferred temperature range. Results from archival satellite pop-up tags indicate that porbeagle can reside in slightly warmer temperatures than those suggested by fishery captures: measurements from 34 porbeagle provided a mean occupied temperature of 11°C, with 50% of their time being spent between 8 and 13°C.

For much of the spring, porbeagle were caught most frequently in waters immediately adjacent to the frontal edge separating cool Shelf waters from warmer offshore waters (Figure 6). Porbeagle were not associated with fronts in the fall fishery, although the temperature occupied was similar to that observed in the spring (5-10°C).

The porbeagle is primarily an opportunistic piscivore with a diet characterized by a wide range of species (Joyce et al. 2002). Teleosts occurred in the majority of stomachs and constituted 91% of the diet by weight. Cephalopods occurred in 12% and were the second most important food category consumed. Diet composition changed seasonally following a migration from deep to shallow water. The relative contribution of groundfish increased with shark size, while the contribution of cephalopods decreased. Other elasmobranchs were occasionally eaten by large porbeagles, but marine mammals and birds were never found in the stomachs (Joyce et al. 2002).

PORBEAGLE SHARK SURVEY

Canada's first fishery-independent survey of porbeagle shark abundance was carried out by Atlantic Canadian fishermen working in conjunction with Fisheries and Oceans Canada scientists in June 2007. The objective of the survey was to provide a baseline for monitoring the population health and abundance of porbeagle and other sharks found off of Atlantic Canada. The second survey was carried out in June 2009, using identical methods. Subsequent surveys will also be carried out using the same design and stations, thus allowing for exact comparison with the 2007 and 2009 surveys.

The 2007 and 2009 shark surveys covered 50 fixed stations in Atlantic Canada stretching from the Canada-U.S. border up to northern NF, an area of more than 200,000 km^2 (Figure 7). Station spacing was not constant throughout the survey area, and tended to be denser on the Scotian Shelf. Pelagic longline gear fit with #8 or #9 J hooks and baited with squid was fished from the surface to the bottom and back, at repeating intervals. A total of 600 hooks were fished each set, with a total soak time of about 6 hours. Scientific staff were present on the survey boats throughout the survey.

Porbeagles (n=865 in 2007; n=488 in 2009) were caught throughout the survey area, but were most common around the deep basins and on the edge of the continental shelf (Figure 7). Catch rates were highest in water temperatures of 6°C (at the depth of the fishing gear) and at depths of 100 m; catch rates were very low in waters colder than 2° and warmer than 10°C. Mature female porbeagles were only caught on the shelf edge. Mean porbeagle FL was 159 cm and 48 kg in weight. However, FL ranged between 83 cm and 245 cm.

Comparison of the survey abundance index with previous commercial catch rates was difficult, since June was not a popular fishing month historically, especially by small vessels. However, it appears that survey catch rates were roughly comparable with those from 2000-2006, as predicted by Gibson and Campana's (2005) population model; catch rates were higher in some areas such as near the shelf edge, and lower in other areas such as the Grand Banks.

No appreciable change in porbeagle abundance would be expected between 2007 and 2009, given the low commercial catches during that period and the low intrinsic population productivity. Indeed, the population abundance model estimates almost identical population abundance in the two survey years. Nevertheless, a comparison of the 2007 and 2009 survey abundance estimates would be interesting. A direct comparison of survey catch rates is not appropriate, since inter-station spacing varied with the region, and was markedly greater on the Grand Banks. In addition, the proportion of the survey stations which were too cold (< 2°C), and thus unsuitable habitat for porbeagles, differed between the survey years. Work is ongoing to provide an appropriate temperature-adjusted and spatially-scaled catch rate for each survey year. Nevertheless, the real value of the shark survey will become apparent when comparing the 2007 and 2009 survey results (which are calibrated against the most recent year of the population model abundance estimate) with those from future survey years, by which time more change in population abundance might be expected.

THE FISHERY

LANDINGS

The commercial landings reported here are the combined reported landings (all countries) for the NW Atlantic (NAFO areas 3-6) from 1961 to 2008 (Table 1). All foreign data after 1978 came from the SFOP or NFOP and are thus considered accurate. Canadian landings data are considered to be relatively accurate, especially after 1996.

Landings rose from about 1,900 t in 1961 to over 9,000 t in 1964 and then fell to less than 1,000 t in 1970 as a result of collapse of the fishery (Table 1; Figure 8). Reported landings remained less than 500 t until 1989, and then increased to a high of about 2000 t in 1992. Landings since 1998 have been restricted by quota, and have been less than 230 t since 2002 (125 t in 2008). Most of the landings are from the directed porbeagle pelagic longline fishery, although with recent quota reductions, the percent landings as bycatch has increased (Table 2). Reported landings of porbeagle in fisheries outside the Scotia-Fundy region are lower and have been under 20 t since 2002 (Table 3). There is almost no recreational fishery for porbeagle sharks.

For the population model, the catch was apportioned to three areas: NF-Gulf = Gulf of St. Lawrence, area north of Laurentian Channel, plus NAFO Division 4Vn; Basin = Basins and inshore regions of Scotian Shelf, and the Shelf edge = area over and around the edge of the Scotian Shelf, plus the Gulf of Maine (Figure 1). The split was accomplished based on location of the reported catch for the years 1989 to 2004, and using the 1988 to 2002 averages for years prior to 1988 (Table 4). Nearly all directed landings since 2003 were from the Basin and Shelf edge areas (Table 4).

LOCATION AND SIZE COMPOSITION OF THE CATCH

Almost all landed porbeagle have been caught on the edge and in the deep basins of the Scotian Shelf since 2005 (Figure 9). Most of this fishing activity took place in the spring.

The TAC for porbeagle in Canada was reduced from 850 t to 250 t in 2002, and further reduced to 185 t beginning in 2006. This reduction in catch quota resulted in the disappearance of the large offshore vessels from the directed fishery, and thus a major contraction in the area fished (Figure 10). Observed catches by Canadian observers in the 1990s were historically distributed along the edge and in the deep basins of the Scotian Shelf, but also in the Gulf of St. Lawrence

and on the Newfoundland Shelf. Most observed catches since the year 2000 have only been along the shelf edges and in the deep basins. All life history stages have roughly similar distributions (Figure 10). Young of the year distribution has been conspicuously absent from the inshore NF shelf since 2000, but this is probably largely due to the closure of the NF mating grounds to directed shark fishing in 2000.

To this point, there has been very little information available on porbeagle catches outside of the Canadian EEZ. Mapping of U.S. 2000-2007 observed catches and tag releases/recaptures (in a roughly 1:1 ratio) (NMFS 2008) indicates that porbeagle are found outside of Canadian waters in substantial numbers, particularly off the northeastern U.S. and off the shelf edge east of the Grand Banks (Figure 11). Young of the year (YOY) porbeagle were particularly prevalent off the eastern edge of the Grand Banks, along the shelf edge in both Canadian and northeastern U.S. waters, and inshore in northeastern U.S. waters. Juveniles were distributed similarly, but with lesser numbers off the Grand Banks. Adults were seldom caught. Given the mixture of tagged and observed sharks used in this database, the mapped distribution is unlikely to be representative of distributional proportions, but does give a good idea of distribution outside of Canadian waters, but within the area fished by U.S. fishermen.

Observed U.S. catch locations of juvenile porbeagles <120 cm FL, excluding observations from the tagging database, show that most juveniles were captured off the continental shelf east of the Grand Banks and off the northeastern U.S. coastline (Figure 12). Given that most of these observations were obtained from the U.S. pelagic longline fishery, the observed distribution largely reflects that of the U.S. high seas fishery. Nevertheless, it reinforces the perspective provided by Figure 11 that juvenile porbeagles often occur in deep water off the continental shelf.

Catch quantities and catch locations of porbeagle by the international fleet on the high seas appear to be incompletely recorded.

The size composition of the Canadian catch has changed since 1990 (Figure 13). When disaggregated by time periods corresponding to an unrestricted fishery (1990-1999), a reduced TAC (2000-2004), and the recent very reduced TAC (2005-2008), the overall size range and modal size of the catch has remained roughly constant at 80-260 cm and 120-140 cm FL, respectively. However, there were noticeably more larger sharks (>140 cm FL) caught before 2005 than after 2005, presumably reflecting a loss of larger sharks from the fishery, as well as the closure of the NF mating grounds.

DISCARDS

The SFOP has maintained 100% coverage of foreign fisheries in the Canadian zone since 1987, thus allowing accurate determinations of foreign shark catch and bycatch. Since 1999, however, essentially all pelagic shark catch and bycatch has been by Canadian vessels, for which observer coverage has been substantially less (on the order of 5% for the large pelagic fishery, and considerably less for groundfisheries). The magnitude of the porbeagle bycatch in each of the Atlantic Canadian fisheries was estimated by fishery, quarter and year from SFOP observations made between 1996-2011. The observed bycatch proportion in each fishery/quarter/year cell was calculated as the weight of the porbeagle discards relative to the weight of the observed kept target catch. After first confirming the absence of temporal trends in the bycatch proportion (see below), the weighted mean proportion (weighted by number of observed sets) across the years 1996-2011 was scaled up to that of the entire fishery by multiplying by the quarterly landings of the target fishery (as reported to the ZIF or MARFIS catch statistics databases) to estimate total discards by fishery, quarter and year. Therefore,

each quarter and fishery was characterized by a unique bycatch proportion, but this proportion was maintained for all years. This method of bycatch estimation is less susceptible to sampling variability or poor sampling than is the year by year method. The assumption that there were no temporal trends in bycatch proportions was tested by plotting the time series for each fishery and quarter. Full details are provided in Campana et al. (2011).

Mortality due to fishing can be partitioned into landed catch, capture mortality (fish that are dead upon retrieval of the fishing gear), and post-release mortality (mortality which occurs after the fish is returned alive to the water). Landed catch is usually known, and capture mortality can be recorded by scientific staff or observers. However, post-release mortality is unknown unless experimentally determined, such as through the use of archival satellite popup tags. Post-release mortality of porbeagle sharks has not yet been measured, and was assumed to be somewhat higher than that of blue sharks (which appear to be a hardier species) (Campana et al. 2009). A total mortality of 50% (capture + post-release) was assumed for non-retained mako and porbeagle sharks.

Observer records were available for most fisheries/quarters/years, but were absent or sporadic when overall catches were low. Based on the proportion of the reported fishery catch which was observed each quarter, the observed catch accounted for 10% of the total swordfish/tuna pelagic longline catch, 7% of the directed longline porbeagle fishery, 6% of the groundfish longline fishery, 2% of the groundfish gillnet fishery, and 11% of the groundfish otter trawl (OTB) fishery. These percentages do not include reported catches for cells for which there were no observer entries, which means that the actual observer coverage percentages could be lower than shown.

Discards of porbeagle (Table 1) tended to be highest during the third quarter of the swordfish/tuna fishery, but averaged less than 10 t per quarter/year in each of the other fisheries.

Annual estimates of shark discards by fishery indicated that the swordfish/tuna fishery accounted for 58% of the porbeagle discards in 2010 (Table 4). However, the groundfish OTB fishery has discarded an average of more than 20 t of porbeagle annually since 1996, while the groundfish longline fishery has discarded an average of 19 t of blue shark annually.

Aggregated across fisheries, an estimated 29 t of non-retained porbeagle died from fishing-related causes in 2010, which is equivalent to 35% of reported landings (Table 4).

Estimated porbeagle discards were minimal (average of <5 t) for all cells except that of the large pelagic longliners between July and December. Observer coverage for this fleet and time period averaged 8% of total landings, but less in terms of number of trips. Total estimated porbeagle discards by the large pelagic fleet in the latter half of the year have averaged 21 t annually since 1996, with an average of 27 t annually since 2000 (Table 5). The size composition of these discards is unknown.

Porbeagle discards by the international high seas fishery are unknown and largely unrecorded.

POPULATION MODEL – INPUT DATA

The data entered into the population model are updated from those presented in Campana et al. (2001) and Gibson and Campana (2005).

COMMERCIAL CATCH RATES (CPUE)

Catch-per-unit-effort (CPUE) is used as the primary index of abundance in this analysis. Calculations of porbeagle CPUE were based on porbeagle-directed longline catches, which account for virtually all historical catches. Initial examination of the catch rate data indicated that the major data sources could be categorized by country (Canada, Faroes), vessel identity (CFV), season, and area fished.

Porbeagle CPUE was calculated in two ways: on the basis of catch weight per hook, and using separate calculations of numbers of mature and immature sharks per hook. Both indices are presented to show trends in abundance, but only the weight per hook index was used to calibrate the population model. Only vessels that fished in a season and area in three or more years were included in the CPUE analyses.

To disaggregate CPUE into rates for immature and mature sharks; Campana et al. (2001) calculated CPUE in terms of ln-transformed numbers per hook. A FL equal to 200 cm is approximately midway between the lengths corresponding to 50% maturity in males and females, and is therefore a proxy for sexually mature porbeagles (Jensen et al. 2002). To calculate catch rate at length, the length composition was determined for each of the three subareas in each of three seasons (January-March, April-June, July-December) based on available measurements each year. Set by set catch rates in terms of weight were converted to numbers based on the mean weight of the length composition of the subarea-season-year cell, then apportioned according to the length frequency. Numbers above 200 cm FL were pooled within a set to form the index for mature sharks, while the remainder were pooled to form the index for immature sharks.

Error plots summarizing the three CPUE data sets are shown in Figure 14. The CPUE by weight data remained relatively high after 2002 in both the Basin and Shelf Edge areas; the NF-Gulf area has not been consistently fished since 2002 (Figure 14a). Much of this trend has apparently been due to catch rates of immature sharks, which have remained relatively high in both the Basin and Shelf Edge after 2002 (Figure 14b). In contrast, the CPUE of mature sharks has continued to decline in the Basin, and been erratic on the Shelf Edge (Figure 14b). The marked decline in CPUE of mature sharks in the NF-Gulf area prior to 2002 has previously been noted (Campana et al. 2001).

At least two issues exist with these CPUE data when deriving an index of abundance. First, the spatial distribution of the fishing effort has decreased markedly in the last few years (Figure 15). Coincidental with this change has been an increase in CPUE after 2002 in the smaller area presently being fished, indicating either increased abundance, increased efficiency, a change in methods or a change in the distribution of porbeagle in recent years. Second, there is little overlap in the vessels that took part in the fishery in the late 1980s and 1990s and those presently fishing (tables 6.1 to 6.3). This issue creates difficulties separating year effects (changes in abundance) from vessel effects (changes in the fleet), and not all vessels fish with the same efficiency (Figure 16). Differences in catchability also exist among seasons (Figure 17).

Catch-per-unit-effort time series are often standardized to correct for differences in the timing and gear used in the fishery (Maunder and Punt 2004) prior to being included in the assessment model. Alternatively, the standardization may be integrated into the assessment model, a method that has been shown to provide greater precision in biomass estimates than when the standardization is done prior to fitting the assessment model (Maunder 2001). The latter approach was used here, whereby the CPUE by weight standardization was integrated into the

assessment model. We fit several models, starting with a simple model with a single catchability coefficient for all vessels in all areas in all seasons, then adding coefficients for area, CFV and season, and adding coefficients for combinations of these variables, in a stepwise fashion (Gibson and Campana 2005). This analysis was done with two weightings of the catch at length data (by changing the assumed sample size). Based on the Akaike Information Criterion (AIC), a model with separate catchability coefficients each vessel, in each area and in each season (each vessel, area and season combination is used as a separate index of abundance) was the best model and was retained for the analyses herein. Full details are shown in Gibson and Campana (2005).

CATCH AT LENGTH

Campana et al. (1999, 2001) describe the porbeagle length data set and standardizations. Over 152,000 length measurements are available for known sex porbeagle, and more are available when sharks of unknown sex are included. To estimate the proportion of the catch by length, we assigned porbeagle to 5 cm length categories ranging from 65 to 285 cm total length. When fitting the model, we used sex specific data for the years: 1995 and 1998 - 2008 for the Basin region; 1988, 1989 to 1996, 1998 to 2000 and 2002 for the NF-Gulf region; and 1961, 1981, and 1990 to 2008 for the Shelf-Edge region. Observed proportions at length and sample sizes are shown in the Results section (figures 20.1 to 20.8).

TAGGING DATA

Descriptions of the porbeagle tagging programs are provided by Campana et al. (1999). Following Campana et al. (2001) and Gibson and Campana (2005), we included only sharks less than 125 cm fork length at the time of tagging and assumed these sharks were either age 0 or age 1. Between 1980 and 1999, a total of 1083 porbeagle sharks in this size category were tagged, resulting in 121 recaptures (Table 7).

POPULATION MODEL

This model is a forward-projecting age- and sex-structured population dynamics model first presented in Campana et al. (2001) and Harley (2002), and then modified in Gibson and Campana (2005). Within this model, the population is projected forward from an equilibrium starting abundance and age distribution by adding recruitment and removing catches. A key assumption in the model is that the porbeagle population was at an unfished equilibrium at the beginning of 1961, when the directed commercial fisheries for porbeagle began. Model parameter estimates (e.g. selectivity parameters and catchability coefficients) are obtained by fitting the model to the available datasets using maximum likelihood.

POPULATION DYNAMICS IN THE MODEL

Of primary interest is the number of fish in year t, of sex s and of age a, denoted $N_{t,s,a}$. The number of fish in each age class in the next year is given by an exponential decay model. Here, the total mortality rate is the sum of the sex and age specific instantaneous natural mortality rate ($M_{s,a}$) and the fishery (g) specific exploitation rate in each year, sex and age class ($u^g_{t,s,a}$).

$$N_{t+1,s,a+1} = N_{t,s,a} e^{-M_{s,a}} \prod_g (1 - u^g_{t,s,a}).$$

Litter size is not thought to vary with age in porbeagle, so the spawner-recruit relationship is expressed in terms of the number of females rather than biomass. Using the letter F to denote the female sex category, the number of female spawners in year t (SSN_t) is a function of $N_{t,F,a}$ and the probability that a female fish of age a is mature at that age ($m_{F,a}$):

$$SSN_t = \sum_a N_{t,F,a} m_{F,a}$$

The life cycle is closed by modelling the number of age-1 fish of each sex in the year t+1 as a function of SSN_t using a Beverton-Holt spawner-recruit (Hilborn and Walters 1992) relationship:

$$N_{t+1,s,1} = \frac{\alpha SSN_t}{1 + \frac{\alpha SSN_t}{R_{asy}}} e^{(\varepsilon_t - \sigma^2/2)} * 0.5$$

Here, α is the slope at the origin, and in the deterministic model is the maximum rate at which female spawners can produce age-1 recruits at low population sizes (Myers et al. 1999), and R_{asy} is the asymptotic recruitment level (expressed as the number of age-1 recruits). R_{asy} is the limit approached by R_t as S_t approaches infinity (Beverton-Holt models are often written in terms of the half saturation constant, K, which is related to R_{asy} by: $R_{asy} = \alpha K$). A 1:1 sex ratio at birth is assumed. Recruitment can vary around the fitted relationship though the log of a recruitment deviate for each year (ε_t), in which case a correction for transformation bias based on the standard deviation of the log recruitment deviate (σ) is applied to each deviate. As written, a lognormal error structure for recruitment (Myers et al. 1995) is assumed. In comparison with the other commonly used 2-parameter stock-recruitment (SR) model, the Ricker model, the Beverton-Holt model has the advantage that R_{asy} can be rescaled and interpreted as an estimate of carrying capacity (Gibson and Myers 2003a; Myers et al. 2001), but is not a precautionary model selection because it typically provides estimates of α (and its related reference points) that are higher than those from the Ricker model (Gibson and Myers 2003b; Myers et al. 1999). Reference points provided herein are therefore not precautionary with respect to SR model selection.

COMMERCIAL FISHERIES

The commercial fisheries are included in the population dynamics through $u^g_{t,s,a}$. This term consists of two separable components: the gear (or fishery) and sex specific selectivity of the commercial fisheries $s^{g,s}_a$ and the exploitation rate of the fully exploited age class by each gear in each year, u^g_t:

$$u^g_{t,s,a} = s^{g,s}_a u^g_t$$

Selectivity was assumed to follow a double half Gaussian selectivity curve:

$$s_a^{g,s} = \begin{cases} \exp\left(\frac{-(a-s_{full}^{g,s})^2}{v_L^{g,s}}\right) & \text{if } a \le s_{full}^{g,s} \\ \exp\left(\frac{-(a-s_{full}^{g,s})^2}{v_R^{g,s}}\right) & \text{if } a \le s_{full}^{g,s} \end{cases}$$

where *g* refers to the commercial fishery (Basin, Shelf-Edge or NF-Gulf). In this model, the age at which fish are fully selected by the fishery is denoted $s_{full}^{g,s}$. The steepness of the decline away from the age at full selectivity is governed by the *v* parameters for the left and right sides of the curve.

The fishery operates throughout much of the year, but for simplicity, we assume the catch is taken during a short time period half way through the year, an approximation attributed to Pope (Quinn and Deriso 1999). We assume that the total catch in each year by each fishery (C_t^g) is known without error. The exploitation rate (proportion of the vulnerable biomass removed) in each fishery in each year is then:

$$u_t^g = \frac{C_t^g}{\sum_{s,a} e^{-0.5M_{s,a}} s_a^{g,s} N_{t,s,a} w_{s,a}}$$

where $w_{s,a}$ is the sex specific weights at age.

INITIAL CONDITIONS

We assume that the population is at an unfished equilibrium population and age structure at the start of the time period (1961). The calculation of the equilibrium population size is provided in the reference point section below.

PREDICTIONS FROM THE MODEL

Parameter estimates are obtained from the model by minimizing the discrepancies between the observed data and predictions from the model. Specifically, we want to obtain predictions of the annual CPUE of sharks in the three fisheries I_t^g, the predicted length composition of the catch in the three fisheries and the predicted number of tagged recaptures for each year.

Under the assumption that CPUE is proportional to abundance, the predicted CPUE's of mature and immature sharks are:

$$I_{t,immature}^g = q^g \sum_{s,a} e^{-0.5M_{s,a}} s_{s,a}^g N_{t,s,a} \quad \text{for } a_f < 11 \text{ and } a_m < 12$$

and

$$I_{t,mature}^g = q^g \sum_{s,a} e^{-0.5M_{s,a}} s_{s,a}^g N_{t,s,a} \quad \text{for } a_f \ge 11 \text{ and } a_m \ge 12.$$

Note that the ages do not correspond directly with the ages of 50% maturity. The mean length at maturity for male and female porbeagle is roughly 200 cm and the split in the data is on this

basis. The ages above correspond to these lengths. These equations were used in Gibson and Campana (2005), but were modified for the current model for CPUE by weight by adding weight at age to the right-hand sum and by increasing the number of *q*'s (one for each boat in each area and each season).

Following Harley (2002), the sex specific predicted length composition in the catch $P_{t,l}^{g,s}$ is a function of the population age composition, the selectivity curves and the distributions of length at age:

$$P_{t,l}^{g,s} = \frac{\sum_a s_a^{g,s} f_{l|a}^s N_{t,s,a}}{\sum_a s_a^{g,s} \sum_l f_{l|a}^s N_{t,s,a}}.$$

Here, the sex-specific length proportions at age ($f_{l|a}^s$) is given by:

$$f_{l|a}^s(l_a^s, \sigma_a^s) = \frac{\delta}{\sqrt{2\pi}\sigma_a^s} \exp\left[\frac{-\left(x_t^s - l_a^s\right)^2}{2\left(\sigma_a^s\right)^2}\right]$$

where δ is the size of the length increment (5 cm in this analysis). Here we used the same growth analysis used in Campana et al. (2001) and Harley (2002), assuming a von Bertalanffy growth model to model the relationship between length and age, as well as a linear relationship between σ_a^s and l_a. Constants are provided in Table 8.

THE TAGGED POPULATION

We assumed that the dynamics of the tagged population were identical to the untagged population. Denoting the number of tagged fish of age *a* that are alive in year *t* as $N_{t,a}^T$, the number of tagged fish in the following year is:

$$N_{t+1,a+1}^T = N_{t,a}^T e^{-M_a}(1-u_{t,a}) + R_{t+1,a+1}^T(1-k),$$

where $R_{t,a}^T$ is the number of tagged fish of age *a* released in year *t* and *k* is the rate of tag loss or mortality associated with tagging assumed to occur shortly after tagging. The expected number of recaptures $T_{t,a}$ is then:

$$T_{t,a} = \xi N_{t,a}^T e^{-0.5M} u_{t,a}.$$

Here, $u_{t,a}$ is the mean of the rates for the fisheries in the three regions and ζ is the reporting rate. Reporting rates of 0.9 were assumed for all years except 2003 and 2004 when (lower) values of 0.75 and 0.70 reflecting comments from the fishing industry.

LIKELIHOOD EQUATIONS

The model was fit to the data by minimizing an objective function (*O.F.V.*) that is the sum of the negative log likelihoods for the CPUE series (ℓ_{CPUE}), the tagging data (ℓ_{tag}) and length compositions in the catches ($\ell_{catch\ comp}$). We used lognormal error structures for the CPUE time series, a Poisson error structure for the tagging data and a robust normal error structure (Fournier et al. 1990) for the proportions at length in the catch. For each fishery, the log-likelihood for the CPUE component of the model is:

$$\ell^{g}_{CPUE} = -\sum_{1}^{n} \ln \sigma^{g} - \frac{1}{2}\log 2\pi - \sum_{t} \frac{(\ln \widetilde{I}^{g}_{t} - \ln I^{g}_{t})^{2}}{2(\sigma^{g})^{2}},$$

where *n* is the number of observations in the series, σ^{g} is the standard deviation of a normal distribution prior to exponentiation and $\widetilde{I}^{g}_{t}$ is the observed CPUE index value in year *t* and region *g*. We used a constant value of 0.3 of all σ^{g} in this analysis. We also used the standard error of each estimate of I^{g}_{t} as an estimate of σ^{g}, an approach that weights the contribution of each year differently based on the precision of the estimate. This alternative made little difference in the overall fits of the model so we retained the constant value of 0.3. This equation was appropriately modified when different grouping of the data were used.

From Harley (2002), for a given gear and sex category, the robust normal log-likelihood for proportions at length in the catch is:

$$\ell^{g,s}_{length\ comp} = 0.5\sum_{t=1}^{Y}\sum_{l=1}^{A}\log(2\pi(\varsigma^{s,g}_{t,l} + 0.1/A_l)) + \sum_{t=1}^{nyears} A_l \log(\tau^{s,g}_{t}) - \sum_{t=1}^{Y}\sum_{l=1}^{A}\log\left[\exp\left\{\frac{-\left(\widetilde{P}^{s,g}_{t,l} - P^{s,g}_{t,l}\right)^{2}}{2\left(\varsigma^{s,g}_{t,l} + 0.1/A_l\right)\tau^{s,g}_{t}}\right\} + 0.01\right],$$

where *Y* is the number with observed proportions at length, A is the number of length categories, $\tau^{s,g}_{t}$ is the sample size and $\varsigma^{s,g}_{t,l}$ is the variance. We set the maximum sample size at 3,000 to keep a few years with very large samples from dominating the fit, and used the variance of the predicted proportions (Fournier et al. 1990):

$$\varsigma^{s,g}_{t,l} = P^{s,g}_{t,l}(1 - P^{s,g}_{t,l}).$$

We used a length-frequency distribution of the sexes combined for some years (see the Data section) with appropriate modifications to the above equations.

The log likelihood for the tagging component of the model is:

$$\ell_{tag} = -\sum_{t,a} T_{t,a} + \sum_{t,a} \widetilde{T}_{t,a} \ln T_{t,a} - \sum_{t,a} \ln(\widetilde{T}_{t,a}!),$$

where ~ is again used to denote the observed data.

The final objective function is then:

$$O.F.V. = -\left(\sum_{g,sizes} \ell_{CPUE}^{g,sizes} + \sum_{g,s} \ell_{catch-comp.}^{g,s} + \ell_{tag} \right)$$

We programmed this model using AD Model Builder (Fournier 1996). AD Model builder uses the C++ auto-differentiation library for rapid fitting of complex non-linear models, has Bayesian and profile likelihood capabilities, and is designed specifically for fitting these types of models.

THE PRODUCTION MODEL AND REFERENCE POINTS

We modelled the population dynamics of porbeagle using two equations: a spawner-recruit relationship that expresses recruitment as a density dependent function of spawner biomass, and the replacement line, the slope of which is the inverse of the rate at which recruits produce replacement spawners. Here, an implicit assumption is made that all density-dependent processes occur between spawning and recruitment. The production model also includes a third component: a yield per recruit relationship. We used the selectivity curves for the Shelf-Edge fishery in the following analysis. All results are therefore specific to that fishery. Results would vary if other selectivity curves had been assumed.

The SR model was discussed in the previous section. We modelled the rate at which recruits produce spawners (the inverse of the slope of the replacement line) by calculating the number of spawners per recruit (SPR_F) as a function of fishing mortality (Shepherd 1982; Mace and Sissenwine 1993, Mace 1994):

$$SPR_F = 0.5 \sum_{1}^{a_{max}} \left[m_a e^{-\sum_{1}^{a-1} (M_{F,a-1} + F_{F,a-1}^{g})} \right] ,$$

where $F_{F,a}^{g}$ is the age and gear specific fishing mortality rate for females. Note that the resulting reference points are specific to the selectivity assumed in the calculation.

The yield per recruit for a given F (YPR_F) is found similarly:

$$YPR_F = \sum_{s} \sum_{1}^{a_{max}} e^{-\left(0.5M_{s,a} + \sum_{1}^{a-1} (M_{s,a-1} + F_{s,a-1}^{g})\right)} \left(1 - F_{s,a}^{g}\right) w_{s,a} .$$

For a given value of F, the spawning biomass produced by the number of recruits in year t is $SSN = SPR_F \cdot R_t$. Equilibrium spawning biomasses and recruitment levels (denoted with asterisks) were found by solving this equation for R_t, and substituting the result in the spawner-recruit model (Quinn and Deriso 1999):

$$\frac{SSN^*}{SPR_F} = \frac{\alpha SSN^*}{1 + \frac{\alpha SSN^*}{R_{asy}}} .$$

The equilibrium spawning biomass (SSB^*) is then:

$$SSN^* = \frac{(\alpha SPR_F - 1)R_{asy}}{\alpha},$$

and the equilibrium number of recruits (R^*) is found by substituting the SSN^* in the spawner-recruit model:

$$R^* = \frac{\alpha SSN^*}{1 + \frac{\alpha SSN^*}{R_{asy}}}.$$

The equilibrium catch (C^*) is R^* multiplied by the yield per recruit for the given value of F:

$$C^* = R^* \cdot YPR_F.$$

Reference points from the spawning biomass per recruit and yield per recruit analyses were found using a grid search across a set of F's {0 to 2.0; increment of 0.0025}. We calculated YPR_F and SPR_F for each value of F, and reference points were then estimated by selected the fishing mortality rate corresponding to the appropriate reference point criterion. The $SPR_{x\%}$ reference points were found by selecting the fishing mortality rate where the SPR_F was x% that of $SPR_{F=0}$.

We estimated five reference points from the production model. The equilibrium spawning biomass in the absence of fishing, SSN_{eq}, was estimated directly from the production model. A spawning biomass of 20% SSN_{eq} is sometimes used as a minimum threshold population size (Beddington and Cooke 1983, Goodyear 1993). $SSN_{20\%}$ was calculated as 20% the equilibrium female spawner abundance in the absence of fishing:

$$SSN_{20\%} = 0.2\frac{(\alpha SPR_{F=0} - 1)R_{asy}}{\alpha}$$

The grid searches were used to find the fishing mortality rate that produces maximum sustainable yield (F_{msy}), the corresponding spawner biomass that produces maximum sustainable yield (SSN_{msy}) and the fishing mortality rate that drives the population to extinction (F_{col}). We estimated F_{msy} by calculating C^* for each value of F, and selecting the value of F where C^* was maximized. SSB_{msy}, the spawning biomass at MSY, was found similarly. The equilibrium fishing mortality rate at which the population goes extinct, F_{col}, is determined by the slope of the SR relationship at the origin α, and is the value of F where $1/SPR_F = \alpha$.

POPULATION VIABILITY ANALYSIS

To assess recovery and timelines for recovery, recovery targets are required. Recovery targets have not yet been established for porbeagle. Here, we assess how differing levels of incidental harm (mortality associated with bycatch in fisheries not targeting porbeagle) affects the recovery timelines relative to two commonly used fishery reference points $SSN_{20\%}$ and $SSNmsy$. These are not recovery targets, but are reference points against which population growth can be evaluated.

Population viability analysis is an important tool which can be used to evaluate recovery potential, recovery trajectories and recovery times. In a population viability analysis (PVA), a population dynamics model is used to determine how the probability of persistence is affected by current conditions and future perturbations (Beissinger and McCullough 2002). The goals of a PVA are to: 1) determine the current viability of a population, 2) identify threats to persistence, and 3) provide a defensible structure for management and legal action. Typically, there are several other benefits of PVA such as identifying information gaps, and directing future research.

A disadvantage of PVA is that it is data intensive and the minimum data required are only available for a few species. For porbeagle, we have estimates of reproductive rates (as characterized via the spawner-recruit model), maturity schedules and mortality rates. However, we do not presently have estimates of variances for these life history parameters or their temporal autocorrelation, two factors than can effect recovery times and population viability. Therefore, we projected the population forward deterministically (no variability added) from the estimated 2009 population size and age-structure using the estimated life history parameters and an assumed bycatch rate. We used the selectivity parameters from the Shelf-Edge fishery for these simulations. Simulations were carried out for 17 levels of bycatch mortality (defined as the proportion of the vulnerable biomass taken as bycatch) ranging from 0.0 to 0.1. Population projections were 100 years in length.

RESULTS

Initial model fitting indicated that, as is often the case with these types of models, estimation of natural mortality was confounded with estimation of selectivity. Additionally, none of the models achieved a robust fit (hessian), so we do not have measures of uncertainty to qualify model results. We are therefore presenting four models fit to the data, each representing a different scenario:

- Model 1: integrated CPUE by weight; constant *M*: *M*=0.1 and 0.2 for immature and mature porbeagle respectively; α estimated in the model
- Model 2: integrated CPUE by weight; *M*= 0.1 and 0.2 for immature and mature porbeagle respectively; constant α =2.0 (lower productivity scenario).
- Model 3: integrated CPUE by weight; *M*= 0.1 and 0.2 for immature and mature porbeagle respectively; constant α =2.5 (intermediate productivity scenario).
- Model 4: integrated CPUE by weight; *M*= 0.1 and 0.2 for immature and mature porbeagle respectively; constant α =3.2 (higher productivity scenario).

Models 2-4 used the same model structure as those of the same name in Gibson and Campana (2005), but Model 1 in the current assessment is different than Model 1 in Gibson and Campana (2005). In the latter, Model 1differed by not integrating CPUE and by using the length frequency twice (once for length composition, and a second time for determining CPUE by maturity stage). For these reasons, Model 1 from Gibson and Campana (2005) was the least preferred model at the time.

FITS TO THE DATA

Based on the maximized likelihoods (Table 9), Model 1 is the most plausible scenario, followed by Model 4. Model 2 is the least plausible of these models. The estimated selectivity of the three

fisheries is roughly similar among the four models (Figure 18; Table 9), with similar parameter estimates for all four models (Table 9).

Differences in fits to the data are also subtle among the models. The predicted CPUE series for porbeagle are similar among the integrated models, although the data show considerable variability around the fitted relationship (figures 19.1 to 19.7). Fits to the catch at length data are shown in figures 20.1 to 20.8, and are again virtually indistinguishable among models. Although no trend is apparent in the catch at length residuals (figures 21.1 to 21.3), the model apparently under-predicts the proportion of larger fish in early years, and the proportion of smaller fish in the later years (Figure 22), although as shown in figures 21.1 to 21.3, the magnitudes of the residuals are relatively small.

Residual patterns for the tagging recaptures are also similar among models (Figure 23). In all models, the catch of younger (< age-4), tagged porbeagles is overestimated, whereas the catch of tagged, older porbeagles is underestimated. Comparison of the log likelihoods (Figure 23) indicates that higher productivity Models 1 and 4 provide better fits than low-medium productivity Models 2 and 3.

The implications of flat-topped rather than dome-shaped selectivity patterns were also explored. The fit of the flat-topped selectivity model was considerably worse (objective function value of 16277 versus the original 13212), and there were extreme residual patterns in proportions at length, indicating that the model was inappropriate. Although the resulting fishing mortality estimates were reduced by about half, and fishable biomass doubled, all fishing mortality reference points were reduced accordingly, producing little net change in recovery trajectory or time.

POPULATION DYNAMICS

Estimates of α were fixed using life history characteristics in Models 2-4, but was estimated to be 3.6 using Model 1 (Table 9). Values of 2, 2.5 and 3.2 were used in the remaining models, and were thought to span the range of plausible values for porbeagle based on life history characteristics (see Discussion). The estimate of the maximum lifetime reproductive rate ($\alpha * SPR_0$) from Model 1 is: 2.9 spawners per spawner, and the assumed values from models 2 to 4 range from 1.6 to 2.6. As expected for sharks, these values are at the lower end of the range for fish populations (Myers et al. 1999), and are indicative of very low population growth rates.

REFERENCE POINTS

Estimates of F_{msy} from the four models range from 0.036 to 0.075 (Table 9), and of F_{col} from 0.075 to 0.160. Estimates of SSN_{msy} decreased with estimated or assumed productivity from 40,089 females for an α of 2.0 to 27,945 females for an α of 3.6. The spawning biomass per recruit reference points $F_{35\%}$ and $F_{45\%}$ met or exceeded F_{col} in most model runs and are not safe reference points for porbeagle fisheries. These reference points were calculated using the selectivities for the Shelf-Edge fishery, but given the similarity to the selectivities for the Basin fishery, reference points for the Basin would likely be close to the values for the Shelf-Edge. Reference points for the NF-Gulf fishery would likely differ, although little fishing is presently occurring in that region (Table 4).

TRENDS IN ABUNDANCE AND EXPLOITATION

Trends in abundance are also roughly similar between the models (Figure 24). Estimates of the number of spawners in 1961 were highest from Model 2. All models suggest an increase in spawner abundance in the late 1970s and early 1980s, although the increase is small. The estimated total number of porbeagle also increases only slightly during the 1980's (Figure 24). Although abundance has been relatively stable since 2002, there has been a very slight increase in abundance of both spawners and recruits since 2006.

Estimates of exploitation rate are also similar among the models (Figure 25). All models estimate exploitation in the Basin region to be 1% or less since 2007 (Table 10). Estimates of the exploitation rate in 2008 for the Shelf-Edge fishery are the same from all models (0.021), which is less than the values expected to produce MSY for any model.

POPULATION STATUS

Estimates of the population size in 2009 (Table 11) range from 196,911 to 206,956 sharks. The estimated number of mature females range from 11,339 to 14,207 (Table 11), or about 6% of the population. The models indicate that the population is about 22% to 27% its size in 1961 (Table 11), and that female spawner abundance is about 12% to 16% of its 1961 level. The models indicate that the reduced quotas since 2002 have more or less halted the decline in population size. Table 12 presents the time series of population size and female spawner abundance.

The total biomass was estimated at around 10,000 mt in 2009 (Table 11). Such a biomass would place the 2009 value at between 20-24% of its value in 1961, and 4-22% higher than it was in the year 2001.

Estimates of the vulnerable biomass in 2009 differ depending on the assumed selectivity as well as among models (Table 13). Assuming the Shelf-Edge selectivity, the models place the vulnerable biomass in 2009 (mid-year) for the entire population at about 4,700–5,100 mt.

RECOVERY TRAJECTORIES

All models indicate that the NW Atlantic porbeagle population can recover if levels of human induced mortality are kept low (Figure 26), with recovery to $SSN_{20\%}$ predicted to occur circa 2012 at harvest rates less than 4%. Estimated recovery times to SSN_{msy} vary depending on the assumed productivity and harvest rate. Based on lower productivity Models 2 and 3, in the absence of human-induced mortality, recovery to SSN_{msy} is expected to occur between 2040 and 2060, whereas higher productivity Models 1 and 4 predict recovery as early as 2028. An incidental harm rate of 4% of the vulnerable biomass is expected to delay recovery to SSN_{msy} to somewhere between 2041 (Model 1, best case scenario) and the 22nd century (Model 2, worst case scenario). Model 1 provides the most optimistic scenario, in part due to the higher estimated productivity and the lower estimated reference points.

DISCUSSION

All of our analyses indicate that the abundance of porbeagle in the NW Atlantic declined during the late 1960s, increased slightly during the late 1970s and early 1980s, and decreased again during the late 1990s. The decline in total and spawner abundance appears to have halted sometime after the quota reductions in 2002, and may have entered the initial stages of

recovery. Population size is expected to increase now that exploitation rates have been lowered, but that recovery times will be slow.

Of the four models presented in this document, statistical considerations (OFV) suggest that Model 1 is the preferred model. Model 1 is also the only model in which α was estimated. Since the α estimate from Model 1 was similar to the fixed value of α incorporated into Model 4, the two models understandably produced similar output. However, these models were also the least precautionary, given that they assumed the highest productivity (highest values of α). In contrast, Model 2 (with the poorest model fit) assumed the lowest productivity, and thus was the most precautionary. All four values of α used in the models were thought to be plausible based on life history characteristics, so there is no obvious means to select among them based on external information. From the perspective of assessing the effects of human-induced mortality, the higher productivity model (Model 1) would result in a higher catch quota than would the more precautionary, lower productivity model (Model 2).

The values of α used in the population models compare favourably with published estimates of juvenile survival in sharks. If a mean litter size of 3.9 is assumed, a value of α of 2 equates to a survival rate of 0.51 between birth and age-1. Using a depletion method with a marked population, Gruber et al. (2001) estimated annual survival of juvenile lemon sharks to vary between 0.38 and 0.65. Most sharks in their study were marked at age-0 although some age-1 and age-2 sharks were also included. Our assumed values include deaths at time of birth and onset of feeding that would not be a part of the Gruber et al. study, so a survival estimate to the lower end of their range is not implausible given the differences in our studies.

The maximum intrinsic rate of increase (r_{max}) for NW Atlantic porbeagle is low relative to estimates for some other sharks. Using the Leslie matrix method (Krebs 1985) and the demographic parameters from Models 2 and 4, r_{max} is estimated to be 0.032 and 0.061 respectively. These values bracket the value of 0.051 estimated by Campana et al (2001). Cortes (2002) estimated a lower value of r_{max} for porbeagle (0.022) due to differences in the assumed natural mortality and longevity. McAllister et al. (2001) derived priors for r_{max} for sandbar shark with medians in the range of 0.07 to 0.09 and for blacktip shark with a median of about 0.125. Smith et al. (1998) estimated r_{max} for several shark species, although due to methodological differences, their results and ours are not directly comparable (our estimate is low relative to their values for most other species). If productivity is being overestimated in our study, the results from Model 2 would be most conservative. Note, however, that although a productivity scenario cannot be selected on the basis of model fit, the estimates of the vulnerable biomass in 2009 are similar among the integrated CPUE models.

As is the case with any complex population model, model verification is often limited to assessing the distribution of the residuals with respect to each factor. Residuals were generally randomly distributed in this model, although the residuals around the tagging data indicated that actual survival and abundance may be higher than predicted by the models. As such, management advice based on the models would be precautionary. However, a comparison of along-cohort catch rates (Paloheimo Z) from Campana et al. (2001) with those of Gibson and Campana (2005) provided a test of model accuracy that was almost independent of the 2005 model results. Those comparisons suggested that the higher productivity scenarios might be closer representations of the porbeagle population than the more conservative model runs. A more rigorous test of model accuracy will become possible when the results of the 2009 shark survey become available, and are compared with the abundance and size composition estimates from the 2007 survey.

Our analyses indicate that the estimated number of mature females is in the range of 11,000 to 14,000 individuals, and in the range of 12% to 16% of its 1961 level. The total population size is thought to be about 22% to 27% its size in 1961 and about 95% to 103% its size in 2001. Total biomass was estimated to be about 10,000 mt in 2009, which is 20-24% of its value in 1961, and 4-22% higher than it was in the year 2001. Spawner abundance in 2009 is about 83% to 103% of its 2001 value. These results are somewhat more optimistic than those reported in Gibson and Campana (2005) for two reasons. First, the current model results reflect four additional years of population growth under reduced exploitation. Indeed, landings since 2004 were less than the 4% harvest rate predicted at the time, due to low market prices. This reduced exploitation provided benefits in terms of stock recovery, albeit marginal. Secondly, the higher CPUE values first observed between 2002 and 2004 have continued to the present, which produced a more lasting effect on modelled abundance. With CPUE being the only index of abundance for model calibration, continued high catch rates should be a good sign. However, an important caveat exists with the contraction of the fishery to the shelf edge and basins where porbeagle density is greatest. Although the incorporation of three separate regions in the model structure was designed to deal with the elimination of the NF-Gulf region of the fishery after the year 2000, it continues to assume that catch rates within the shelf edge and basin regions are randomly distributed in space; if that assumption is false, model output may be overly optimistic. We note, however, that the shark surveys do not suggest that overall population distribution has unduly contracted, or that areas of high porbeagle density are restricted to the area now being fished.

All analyses indicate that this porbeagle population can recover at modest fishing mortalities, but that the time horizon for recovery is sensitive to the amount of human-induced mortality. All population models predict recovery to $SSN_{20\%}$ in less than five years in the absence of human-induced mortality, and to occur before 2014 if the human-induced mortality rate is 4% of the vulnerable biomass. Of the four models, Model 2 is the least optimistic due to the lower assumed productivity. This model predicts that recovery will occur if human-induced mortality is less than 4% of the vulnerable biomass, but not at 8%. Under this model, recovery to SSN_{msy} is predicted to take over 100 years at exploitation rates of 4% of the vulnerable biomass. These estimates are conditional on the assumed selectivity. Assuming the Shelf-Edge selectivity, Models 1, 3 and 4 (all of which fit better than Model 2) predict that keeping the rate of human-induced mortality to less than 4% of the vulnerable biomass would be precautionary and would keep expected recovery times to SSN_{msy} on the order of decades.

Analyses presented herein indicate the current population is not so small that random factors will threaten the population. Although the recent trajectory of the stock is nearly flat, the expectation is that abundance will increase as spawner abundance increases due to maturity of juveniles, so that survival or recovery is not in jeopardy in the short term. The known sources of human-induced mortality (bycatch) for this population are under management control and, assuming they can be monitored and enforced, are unlikely to increase during the near term. As a result, a low level of human-induced mortality will still allow the population to increase towards recovery thresholds and, if appropriately controlled, will not jeopardise the survival or recovery of the species. Unknown, and hence unregulated, catches of porbeagle on the high seas remain the wild card in the recovery of this population.

REFERENCES

Aasen, O. 1963. Length and growth of the porbeagle (*Lamna nasus*) in the North West Atlantic. Rep. Norwegian Fish. Mar. Invest. 13:20-37.

Beddington, J.R., and J.G. Cooke. 1983. The potential yield of fish stocks. U.N. FAO Fisheries Tech. Paper 242. Rome, Italy.

Beissinger, S.R., and S.R. McCullough. 2002. Population viability analysis. The University of Chicago Press, Chicago, Illinois, USA.

Campana, S.E., and W.N. Joyce. 2004. Temperature and depth associations of porbeagle shark (*Lamna nasus*) in the northwest Atlantic. Fish. Oceanogr. 13:52-64.

Campana, S.E., J. Brading, and W. Joyce. 2011. Estimation of pelagic shark bycatch and associated mortality in Canadian Atlantic fisheries. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/067: vi + 19 p.

Campana, S.E., W. Joyce, and M. Fowler. 2010. Subtropical pupping ground for a cold-water shark. Can. J. Fish. Aquat. Sci. 67:769-773.

Campana, S. E., W. Joyce, and M.J. Manning. 2009. Bycatch and discard mortality in commercially caught blue sharks *Prionace glauca* assessed using archival satellite pop-up tags. Mar. Ecol. Prog. Ser. 387:241-253.

Campana, S., W. Joyce, and L. Marks. 2003. Status of the porbeagle shark (*Lamna nasus*) population in the northwest Atlantic in the context of species at risk. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/007.

Campana, S.E., L.J. Natanson, and S. Myklevoll. 2002a. Bomb dating and age determination of large pelagic sharks. Can. J. Fish. Aquat. Sci. 59:450-455.

Campana, S., L. Marks, W. Joyce, and S. Harley. 2001. Analytical assessment of the porbeagle shark (*Lamna nasus*) population in the northwest Atlantic, with estimates of long-term sustainable yield. DFO Can. Sci. Advis. Sec. Res. Doc. 2001/067.

Campana, S., L. Marks, W. Joyce, P. Hurley, M. Showell, and D. Kulka. 1999. An analytical assessment of the porbeagle shark (*Lamna nasus*) population in the northwest Atlantic. DFO Can. Stock Assess Sec. Res. Doc. 99/158.

Campana, S., W. Joyce, L. Marks, L.J. Natanson, N.E. Kohler, C.F. Jensen, J.J. Mello, H.L. Pratt Jr., and S. Myklevoll. 2002b. Population dynamics of the porbeagle in the northwest Atlantic Ocean. North Am. J. Fish. Management 22:106-121.

Campana, S.E., W. Joyce, L. Marks, P. Hurley, L. Natanson, N.E. Kohler, C.F. Jensen, J.J. Mello, H.L. Pratt Jr., S. Myklevoll, and S. Harley. 2008. The rise and fall (again) of the porbeagle shark population in the Northwest Atlantic. *In* Sharks of the Open Ocean: Biology, Fisheries and Conservation. Edited by M.D. Camhi, E.K. Pikitch, and E.A. Babcock. Blackwell Publishing, Oxford, U.K. pp. 445-461.

Cassoff, R.M., S.E. Campana, and S. Myklevoll. 2007. Changes in baseline growth and maturation parameters of Northwest Atlantic porbeagle, *Lamna nasus*, following heavy exploitation. Can. J. Fish. Aquat. Sci. 64:19-29.

Cortes, E. 2002. Incorporating uncertainty into demographic modeling: Application to shark populations and their conservation. Cons. Biol. 16:1048-1062.

COSEWIC. 2004. COSEWIC assessment and status report on the porbeagle shark *Lamna nasus* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa, Ontario, Canada. viii + 43 p.

Fournier, D. 1996. An introduction to AD Model Builder for use in nonlinear modelling and statistics. Otter Research Ltd., Nanaimo, BC, Canada.

Fournier, D., J.R. Sibert, J. Majkowski, and J. Hampton. 1990. MULTIFAN a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna. Can. J. Fish. Aquat. Sci. 47:301-317.

Francis, M.P., and J.D. Stevens. 2000. Reproduction, embryonic development, and growth of the porbeagle shark, *Lamna* nasus, in the southwest Pacific Ocean. Fish. Bull. 98:41-63.

Francis, M.P., S.E. Campana, and C.M. Jones. 2007. Age under-estimation in New Zealand porbeagle sharks (*Lamna* nasus): is there an upper limit to ages that can be determined from shark vertebrae? Mar. Freshw. Res. 58:10-23.

Gibson, A.J.F., and S.E. Campana. 2005. Status and recovery potential of porbeagle shark in the Northwest Atlantic. CSAS Res. Doc. 2005/053.

Gibson, A.J.F., and R.A. Myers. 2003a. A meta-analysis of the habitat carrying capacity and the maximum lifetime reproductive rate of anadromous alewife in eastern North America. *In* Biodiversity, Status, and Conservation of the World's Shads. Edited by K. E. Limburg, and J.R. Waldman. American Fisheries Society Symposium 35. American Fisheries Society, Bethesda, MD. pp. 211-221

Gibson, A.J.F., and R.A. Myers. 2003b. Biological reference points for anadromous alewife (*Alosa pseudoharengus*) fisheries in Atlantic Canada. Can. Tech. Rep. Fish. Aquat. Sci. 2468.

Goodyear, C.P. 1993. Spawning stock biomass per recruit in fisheries management: foundation and current use. *In* Risk evaluation and biological reference points for fisheries management. Edited by S.J. Smith, J.J. Hunt, and D. Rivard. Can. Spec. Publ. Fish. Aquat. Sci. 120. pp. 67-82.

Gruber, S.H., J.R.C. de Marignac, and J.M. Hoenig. 2001. Survival of juvenile lemon sharks at Bimini, Bahamas, estimated by mark-depletion experiments. Trans. Am. Fish. Soc. 130:376-384.

Harley, S.J. 2002. Statistical catch-at-length model for porbeagle shark (*Lamna nasus*) in the Northwest Atlantic. ICCAT Coll. Vol. Sci. Pap. SCRS/2001/073 1314-1332.

Hilborn, R., and C.J. Walters. 1992. Quantitative fisheries stock assessment: Choice, dynamics and uncertainty. Chapman and Hall, New York, NY, USA.

Jensen, C.F., L.J. Natanson, H.L. Pratt, N.E. Kohler, and S. Campana. 2002. The reproductive biology of the porbeagle shark (*Lamna nasus*) in the western North Atlantic Ocean. Fish. Bull. 100:727-738.

Joyce, W.N., S.E. Campana, L.J. Natanson, N.E. Kohler, H.L. Pratt Jr., and C.F. Jensen. 2002. Analysis of stomach contents of the porbeagle shark (*Lamna nasus*) in the northwest Atlantic. ICES J. Mar. Sci. 59:1263-1269.

Krebs, C.J. 1985. Ecology: the experimental analysis of distribution and abundance. 3rd ed. Harper and Row, New York, NY, USA.

Mace, P.M. 1994. Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. Can. J. Fish. Aquat. Sci. 51:110-122.

Mace, P.M., and M.P. Sissenwine. 1993. How much spawning per recruit is enough? *In* Risk evaluation and biological reference points for fisheries management. Edited by S.J. Smith, J.J. Hunt and D. Rivard. Can. Spec. Publ. Fish. Aquat. Sci. 120. pp. 101-118.

McAllister, M.K., E.K. Pikitch, and E.A. Babcock. 2001. Using demographic methods to construct Bayesian priors for the intrinsic rate of increase in the Schaefer model and implications for stock rebuilding. Can. J. Fish. Aquat. Sci. 58:1871-1890.

Maunder, M.N. 2001. A general framework for integrating the standardization of catch per unit of effort into stock assessment models. Can. J. Fish. Aquat. Sci. 58:795-803.

Maunder, M.N., and A.E. Punt. 2004. Standardizing catch and effort data: A review of recent approaches. Fish. Res. 70:141-159.

Myers, R.A., J. Bridson, and N.J. Barrowman. 1995. Summary of worldwide stock and recruitment data. Can. Tech. Rep. Fish. Aquat. Sci. 2024: iv + 327 p.

Myers, R.A., B.R. MacKenzie, K.G. Bowen, and N.J. Barrowman. 2001. What is the carrying capacity of fish in the ocean? A meta-analysis of population dynamics of North Atlantic cod. Can. J. of Fish. Aquat. Sci. 58:1464-1476.

Myers, R.A., K.G. Bowen, and N.J. Barrowman. 1999. The maximum reproductive rate of fish at low population sizes. Can. J. Fish. Aquat. Sci. 56:2404-2419.

Natanson, L.J., J.J. Mello, and S.E. Campana. 2002. Validated age and growth of the porbeagle shark, *Lamna nasus*, in the western North Atlantic Ocean. Fish. Bull., U.S. 100:266-278.

NMFS. 2008. Draft Amendment 1 to the Consolidated Atlantic Highly Migratory Species Fishery Management Plan Essential Fish Habitat. NOAA, NMFS, Office of Sustainable Fisheries, Highly Migratory Species Management Division, Silver Spring, MD, USA.Pub. Doc. pp. 343.

O'Boyle, R.N., G.M. Fowler, P.C.F. Hurley, W. Joyce, and M.A. Showell. 1998. Update on the status of NAFO SA 3-6 porbeagle shark (*Lamna nasus*). CSAS Res. Doc. 98/41, Fisheries and Oceans, Canada.

O'Boyle, R., M. Fowler, P. Hurley, M. Showell, and W. Stobo. 1996. Observations on porbeagle shark (*Lamna nasus*) in the North Atlantic. DFO Atl. Fish. Res. Doc. 96/24.

Quinn, T. J. II and R. B. Deriso. 1999. Quantitative Fish Dynamics. Oxford University Press. New York.

Shepherd, J.G. 1982. A versatile new stock-recruitment relationship of fisheries and construction of sustainable yield curves. J. Cons. Perm. Int. Explor. Mer 40: 67-75.

Smith, S.E., D.W. Au, and C. Show. 1998. Intrinsic rebound potentials of 26 species of Pacific sharks. Mar. Freshwater Res. 49:663-678.

Stevens, J.D. 1990. Further results from a tagging study of pelagic sharks in the north-east Atlantic. J. Mar. Biol. Ass. U.K. 70:707-720.

Table 1. Reported landings (mt) by country for NAFO areas 2 to 6. Canadian landings have been converted to live equivalent weight, which differs in some cases from the live weight recorded in the statistics.

Northwest Atlantic (NAFO Areas 2 - 6)

Year	Canada	Faroe Is	France	Iceland	Japan	Norway	Spain	USSR	USA	Total
1961	0	100				1824				1924
1962	0	800				2216				3016
1963	0	800				5763				6563
1964	0	1214		7		8060				9281
1965	28	1078				4045				5151
1966	0	741				1373				2114
1967	0	589			36					625
1968	0	662			137	269				1068
1969	0	865			208					1073
1970	0	205			674					879
1971	0	231			221					452
1972	0	260				87				347
1973	0	269								269
1974	0									0
1975	0	80								80
1976	0	307								307
1977	0	295								295
1978	1	121								122
1979	2	299								301
1980	1	425								426
1981	0	344			3					347
1982	1	259			1					261
1983	9	256			0					265
1984	20	126			1	17				164
1985	26	210			0					236
1986	24	270			5			1		300
1987	59	381			16			0	12	468
1988	83	373			9			3	32	500
1989	73	477			9			3	4	566
1990	78	550			8			9	19	664
1991	329	1189			20			12	17	1567
1992	814	1149			7			8	13	1991
1993	920	465			6			2	39	1432
1994	1573				2				3	1578
1995	1348		7		4				5	1364
1996	1043		40		9				8	1100
1997	1317		13		2		3		2	1337
1998	1054		20		0		9		12	1095
1999	955				6		3		3	967
2000	899		13		24		5			941
2001	499		2		25		3			528
2002	229		1		0		5		0	236
2003	139		2		0		2		0	143
2004	218		4		0		5		1	228
2005	203						7		0	210
2006	190						9		0	199
2007	93						6			99
2008	125						37			162
2009	62									62
2010	83									83
2011	30									30

Notes:

- **Northwest Atlantic** data for 1950-1960 is from FAO (ICCAT Report of Shark Working Group, Miami, 26-28 February 1996), 1964-1986 from NAFO, 1987-2004 from Scotia-Fundy and NF IOP (includes landings and discards), and 2000-2008 from FAO Fishstat Plus v 2.32 Capture Production March 2008, NAFO Database 21B or ICCAT Task 1 Dataset 2009
- **Canada** data for 1961-1990 is from NAFO, 1991-2002 from DFO Zonal Statistics File, corrected to appropriate live equivalent weight, and 2003-2012 from DFO MARFIS
- **Faroe Island (Is)** data for 1961-1963 is from FAO (ICCAT Report of Shark Working Group, Miami, 26-28 February 1996)
- **France** data is from FAO Statistics (1998), 2000-2006 from FAO Fishstat Plus v 2.32
- Northwest Atlantic data for 2000-2006 (**Japan**) from NAFO Database 21B , catch for code 469, large sharks
- **Norway** data for 1961-1986 is from NAFO
- NAFO catch data for **Spain** for 2005 (231 mt) and 2006 (230 mt) were errors, and not reported here
- Northwest Atlantic data for **USA** from 1961-1994 is from FAO (ICCAT Report of Shark Working Group, Miami, 26-28 February 1996)

Table 2. Porbeagle bycatch (kg) in Canadian Scotia-Fundy fisheries.

Year	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
TAC	850,000	850,000	250,000	250,000	250,000	250,000	185,000	185,000	185,000	185,000	185,000	185,000
Groundfish fixed gear 45-65	997	789	958	2400	2031	1196	509	851	848	1119	3957	1064
Groundfish fixed gear <45	4743	6925	13141	13041	14344	15286	9,870	18,258	14,409	20,396	34,628	15,419
Groundfish inshore					56	197	687	100	170	1106		
Groundfish midshore	461	518	697	1384	101	166		780	448			
Groundfish offshore	191	285		220	600	1131	594	323	288	229	422	675
Groundfish unspecified	456	1059	1184	1105	1010	2747	3,908	1,597	317	1628	701	
Total Groundfish	6848	9576	15980	18150	18141	20723	15,568	21,909	16,481	24,479	39,706	17,158
Directed porbeagle	870741	476703	172001	86059	172520	161997	123,913	49,965	87,637	28,535	17,415	4,622
Swordfish	5482	9582	18939	29160	22155	11641	14,157	9,120	10,533	6,510	22,967	6,689
Tuna	1266	577	18435	5558	6156	8569	36,221	12,245	10,137	921	680	1,606
Herring		256			23							
Total	884337	496694	225355	138927	218995	202930	189,859	93,239	124,788	61,567	82,892	30,076
Total from bycatch	13596	19991	53354	52868	46475	40933	65,946	43,274	37,151	31,910	63,353	25,453
Percent total from bycatch	2%	4%	24%	38%	21%	20%	35%	46%	30%	52%	76%	85%

Table 3. Porbeagle catch (kg) in Canadian fisheries outside of Scotia-Fundy.

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008
Newfoundland fixed gear	141	946	1,851	1,071	142	27	105		
Newfoundland mobile gear			40						
Gulf (all gears)	18,976	1,192	11,566	2,565	12,968	52	691	55	
Gulf (unspecified shark)[1]	8,378	6,945	8,799	5,090	3,512	3,347			
USA (all gears)[2]	3,595	785	1,813						

[1] may include porbeagle
[2] landings only

Table 4. Proportion of the reported, directed porbeagle landings from each of three regions.

Year	Basin	NF-Gulf	Shelf-Edge
1988	0.03	0.33	0.64
1989	0.09	0.35	0.56
1990	0.32	0.25	0.43
1991	0.18	0.42	0.40
1992	0.12	0.49	0.39
1993	0.12	0.42	0.46
1994	0.20	0.27	0.53
1995	0.08	0.43	0.48
1996	0.14	0.33	0.54
1997	0.14	0.32	0.54
1998	0.08	0.34	0.58
1999	0.15	0.22	0.63
2000	0.17	0.39	0.44
2001	0.11	0.24	0.66
2002	0.43	0.22	0.35
2003	0.51	0.02	0.47
2004	0.20	0.02	0.78
2005	0.31	0.00	0.69
2006	0.54	0.00	0.45
2007	0.48	0.09	0.43
2008	0.17	0.01	0.82
Average	0.22	0.25	0.54

Table 5. Estimated bycatch, discards and discard mortality of porbeagle by Canadian fisheries.

	Discards (mt)															
Source	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Estimated Total Catch	1107	1324	1015	1036	980	591	330	257	336	314	293	181	209	134	161	171
Estimated Discard Catch	63	72	68	61	56	59	60	61	65	69	62	58	55	53	57	59
Estimated Post-release Mortality	32	36	34	31	28	30	30	30	32	35	31	29	27	26	29	29
Reported Landings	1014	1223	916	951	884	497	225	139	219	203	190	93	125	62	83	30
Sum of Landings + Post-release mortality	1046	1259	950	982	913	526	256	169	252	237	221	122	152	88	111	59
	Discards (mt)															
Fishery	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Swordfish and Tuna LL	19	26	22	22	19	20	28	31	35	40	38	33	30	27	33	37
Porbeagle LL	8	11	10	10	9	7	2	1	2	2	1	1	1	0	0	0
Groundfish LL	4	4	4	3	3	3	3	3	2	2	2	3	3	2	2	2
Groundfish Gillnet	2	5	4	3	4	3	2	4	3	3	1	1	1	2	1	1
Groundfish OTB	29	27	29	23	21	26	25	21	22	22	19	20	20	21	21	18
Total Discards	63	72	68	61	56	59	60	61	65	69	62	58	55	53	57	58

Table 6.1. Distribution of sets that have reported catch (weight) and effort, by vessel and year, in the Basin area. Totals are the number of sets.

CFV	1981	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	Total
1					X	X	X																64
2	X	X	X	X	X	X	X																110
3																					X		1
4										X	X												29
5																				X	X		8
6															X								3
7										X	X	X	X						X				42
8										X	X	X	X	X									95
9						X	X	X	X	X	X	X	X	X									100
10									X	X	X	X	X	X	X	X			X	X			89
11											X												27
12										X	X												6
13										X	X												27
14										X	X												14
15									X			X											7
16																				X			1
17											X												2
18																				X	X		4
19								X		X	X	X											13
20																				X			2
21								X	X	X	X	X	X	X		X		X					52
22																				X	X		18
23																						X	3
24																						X	4
25									X					X									2
26							X	X	X	X	X	X	X		X								55
27												X	X	X	X	X	X	X	X	X	X	X	153
28												X	X	X	X	X					X		111
29												X	X	X		X	X			X			37
30																X			X	X	X		24
31																	X	X	X	X	X	X	34
32																			X	X			3
33																					X		1
34																					X		1
35					X	X	X	X	X														114
36																			X				2
Total	6	2	3	35	93	74	66	88	47	94	146	94	118	108	66	37	15	26	37	60	31	12	1258

Note: CFV = vessel identity

Table 6.2. Distribution of sets with reported catch (weight) and effort, by vessel and year, in the NF-Gulf area. Totals are the number of sets.

CFV	1981	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	Total
1						X	X	X										202
2	X	X	X	X	X	X	X	X										415
3															X			17
4							X	X	X	X	X	X	X	X	X	X		395
5												X						6
6											X			X				9
7								X	X	X	X	X	X	X	X	X	X	676
8						X	X	X	X	X								241
Total	8	61	67	55	68	167	306	245	187	209	78	122	116	88	138	33	13	1961

Table 6.3. Distribution of sets with reported catch (weight) and effort, by vessel and year, in the Shelf Edge area. Totals are the number of sets.

CFV	1981	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	Total
1						X	X	X																173
2	X																							19
3	X	X	X	X	X	X	X	X																499
4																						X		1
5												X		X		X								23
6																					X			2
7																X								12
8											X													1
9										X	X	X	X	X	X									88
10							X	X	X	X	X	X	X	X	X	X								656
11													X	X	X	X	X	X			X			116
12													X											5
13												X	X											3
14											X	X												8
15													X											10
16												X		X										17
17																					X			1
18										X	X		X											4
19																					X			1
20											X	X	X	X	X	X	X		X	X	X			214
21															X									12
22								X	X	X	X	X	X	X	X	X	X							467
23																			X		X			5
24													X	X	X	X								43
25														X					X	X		X		19
26																					X			2
27																	X	X	X		X	X		16
28																			X	X		X	X	15
29																						X		1
30																							X	11
31						X	X	X	X	X														207
	86	58	69	62	58	134	203	192	199	171	220	218	265	269	175	147	22	8	33	15	22	12	13	2651

Table 7. Number of porbeagle sharks tagged in the USA and Canadian tagging programs between 1980 and 1999 and the number and timing of recaptures of porbeagle that were tagged when under 125 cm in fork length (from Gibson and Campana 2005).

Year	Number Tagged		Year recaptured																			
Tagged	Total	<125cm FL	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	**Total**
USA																						
80		1																				0
81		5																				0
82		5			1																	1
83		3																				0
84		5																				0
85		7																				0
86		20					1		1				1									3
87	83	25						1								1						2
88	55	11								2				1								3
89		1											1									1
90		0																				0
91		10										1										1
92		16												1	1	1			1			4
93	132	106													3	2	1	5	2	3		16
94	135	131													2	10	6	6	4	5	2	35
95	118	116															4	3		4		11
96	44	37																2		1		3
97	135	99																1		4	2	7
98	91	53																		1	1	2
99	151	148																		3	2	5
USA Total	944	801	0	0	1	0	1	1	1	2	0	1	2	2	6	14	11	17	7	21	7	94
Canada																						
94	40	40														1		3				4
95	179	179															4	3	6	6		19
96	37	37																1		1	1	3
97	23	23																			1	1
98	5	5																				0
Can. Total	284	284													0	1	4	7	6	7	2	27

Table 8. Constants used in the assessment model (from Gibson and Campana 2005).

Component	Parameter	Females	Males
Growth	L_∞	309.8	257.7
(Von Bertalanffy)	t_0	0.061	0.080
	k	-5.90	-5.78
Growth variability	b_0	12.05	11.05
(linear)	b_1	4E-4	0.0048
Length to weight	b_i	5E-5	5E-5
conversion	b_{ii}	2.713	2.713
Maturity	A_{50}	13	8
(logistic)	a	-13.57	-6.07
	b	1.042	0.75
Age for splitting CPUE		11	12

Table 9. Parameter maximum likelihood estimates and reference points obtained from four models fit to the porbeagle data. The models differ in the assumed productivity. Reference points are calculated using the selectivity curves for the Shelf Edge fishery.

		Model 1	Model 2	Model 3	Model 4
Differing assumptions:		σ estimated	σ =2.0	σ =2.5	σ =3.2
OFV		13,139	13,269[a]	13,212[a]	13,160[a]
Spawner – Recruit	Rasym	135,525	280,675	195,399	149,018
	alpha	3.6	2[a]	2.5[a]	3.2[a]
	SPRF0	0.808	0.808	0.808	0.808
Selectivity (Basin)	B_SfullF	2 (bound)	2 (bound)	2 (bound)	2 (bound)
	B_SfullM	2.063	2.072	2.068	2.064
	B_varLestF	0.243	0.254	0.248	0.243
	B_varLestM	0.979	1.014	0.987	0.968
	B_varRestF	33.040	29.534	30.926	32.550
	B_varRestM	216.007	168.370	185.564	207.195
Selectivity (NF-Gulf)	N_SfullF	10.486	9.970	10.148	10.375
	N_SfullM	15.725	14.277	14.739	14.728
	N_varLestF	35.153	34.331	34.51	35.008
	N_varLestM	65.126	58.842	60.370	57.423
	N_varRestF	23.262	24.208	23.881	23.510
	N_varRestM	2.873	9.975	7.517	8.048
Selectivity (Shelf Edge)	E_SfullF	2 (bound)	2 (bound)	2 (bound)	2 (bound)
	E_SfullM	10.032	9.648	9.663	9.850
	E_varLestF	0.314	0.338	0.326	0.316
	E_varLestM	95.230	97.473	93.360	93.467
	E_varRestF	53.125	45.45	48.283	51.573
	E_varRestM	23.483	22.086	24.159	24.678
Catchability	logqCPUE	-8.388[b]	-8.473[b]	-8.433[b]	-8.401[b]
Tag loss/mortality	proportion	0.608	0.591	0.601	0.607
Reference Population Sizes	SSNeq	71,858	86,447	79,722	73,838
	20% SSNeq	14,372	17,290	15,945	14,768
	Req	88,933	106,989	98,667	91,384
	SSNmsy	27,945	40,089	34,573	30,009
Reference Fishing Mortality Rates	Fmsy	0.075	0.036	0.051	0.067
	Fcol	0.160	0.075	0.108	0.142
	F35%	0.157	0.166	0.163	0.157
	F45%	0.119	0.125	0.122	0.119

Note: OFV = objective function value

[a] *constants (not estimated)*
[b] *average catchabilities (q) for 59 CPUE series*

Table 10. Estimates of recent exploitation rates (proportion of vulnerable biomass taken by the fishery).

	Year	Model 1	Model 2	Model 3	Model 4
Basin	2006	0.022	0.023	0.022	0.022
	2007	0.009	0.010	0.010	0.009
	2008	0.004	0.005	0.005	0.005
NF Gulf	2006	0.000	0.000	0.000	0.000
	2007	0.002	0.002	0.002	0.002
	2008	0.000	0.000	0.000	0.000
Shelf	2006	0.018	0.018	0.018	0.018
	2007	0.008	0.009	0.008	0.008
	2008	0.021	0.021	0.021	0.021

Table 11. Estimates of population size and total biomass (mt) obtained from four models fit to the porbeagle data. See text for model descriptions.

		Model 1	Model 2	Model 3	Model 4
Differing assumptions:		σ estimated	σ =2.0	σ =2.5	σ =3.2
1961	SSN	71,858	86,447	79,722	73,838
	N	760,620	915,048	843,866	781,582
	Biomass	41,744	50,219	46,312	42,894
1971	SSN	17,439	33,087	25,947	19,868
	N	291,174	422,212	362,599	310,002
	Biomass	11,958	19,541	16,048	13,013
1981	SSN	20,842	35,013	28,561	22,759
	N	284,362	383,292	339,358	299,446
	Biomass	14,292	20,404	17,672	15,220
1991	SSN	20,935	30,661	26,385	22,516
	N	347,711	397,555	374,428	354,463
	Biomass	16,587	20,335	18,636	17,131
2001	SSN	10,999	17,031	14,377	12,062
	N	190,024	206,680	198,163	192,162
	Biomass	8,082	9,664	8,908	8,299
2009	SSN	11,339	14,207	12,886	11,809
	N	206,956	196,911	198,970	204,482
	Biomass	9,890	10,078	9,903	9,891
2009/1961	SSN	0.119	0.164	0.162	0.160
	N	0.272	0.215	0.236	0.262
	Biomass	0.237	0.201	0.214	0.231
2009/2001	SSN	1.031	0.834	0.896	0.979
	N	1.089	0.953	1.004	1.064
	Biomass	1.223	1.043	1.112	1.192

Table 12. Estimates of population abundance (N) and female spawning stock number (SSN) by year obtained from four models fit to the porbeagle data.

	Model 1			Model 2			Model 3			Model 4	
Year	SSN	N	Year	SSN	N	Year	SSN	N	Year	SSN	N
1961	71858	760620	1961	86447	915048	1961	79722	843866	1961	73838	781582
1962	70398	724557	1962	85227	877843	1962	78424	807113	1962	72452	745310
1963	67657	671014	1963	82898	822375	1963	75959	752425	1963	69838	691436
1964	61379	553681	1964	77528	700937	1964	70286	632648	1964	63834	573387
1965	51009	387974	1965	68555	530187	1965	60827	463948	1965	53855	406769
1966	41668	307139	1966	60241	448183	1966	52131	382609	1966	44764	325811
1967	34701	290759	1967	53526	431292	1967	45305	366282	1967	37855	309646
1968	29639	306840	1968	48034	444711	1968	39942	381091	1968	32692	325615
1969	24867	304562	1969	42560	440548	1969	34697	378099	1969	27753	323422
1970	20788	297350	1970	37519	431220	1970	29988	370059	1970	23454	316271
1971	17439	291174	1971	33087	422212	1971	25947	362599	1971	19868	310002
1972	14790	291883	1972	29405	419030	1972	22653	361326	1972	17001	310380
1973	12712	290825	1973	26455	413907	1973	20037	358161	1973	14739	308926
1974	11235	287867	1974	24404	406990	1974	18206	353145	1974	13134	305554
1975	10530	287925	1975	23567	403304	1975	17419	351252	1975	12384	305197
1976	10728	284482	1976	24077	396814	1976	17817	346285	1976	12626	301428
1977	11842	277123	1977	25773	387016	1977	19315	337778	1977	13852	293816
1978	13729	272977	1978	28231	380654	1978	21603	332604	1978	15871	289422
1979	16112	276039	1979	30934	381371	1979	24246	334521	1979	18352	292174
1980	18450	279657	1980	33263	382093	1980	26643	336605	1980	20734	295337
1981	20482	284362	1981	35013	383292	1981	28561	339358	1981	22759	299446
1982	22153	293079	1982	36203	388045	1982	29988	345811	1982	24382	307469
1983	23350	304893	1983	36801	395483	1983	30861	355097	1983	25503	318515
1984	23954	317026	1984	36769	402859	1984	31113	364468	1984	26018	329817
1985	24089	330796	1985	36266	411592	1985	30890	375311	1985	26058	342717
1986	23751	341865	1986	35342	417397	1986	30223	383327	1986	25629	352886
1987	23113	350038	1987	34191	420200	1987	29298	388392	1987	24911	360152
1988	22309	353019	1988	32959	417839	1988	28258	388295	1988	24039	362240
1989	21605	353904	1989	31899	413519	1989	27361	386192	1989	23278	362260
1990	21102	352393	1990	31097	407003	1990	26697	381821	1990	22727	359925
1991	20935	347711	1991	30661	397555	1991	26385	374428	1991	22516	354463
1992	20342	326215	1992	29848	371532	1992	25680	350363	1992	21902	332225
1993	19223	298943	1993	28536	340072	1993	24466	320729	1993	20778	304286
1994	18404	282670	1994	27471	320080	1994	23515	302385	1994	19938	287468
1995	17648	261331	1995	26416	295351	1995	22593	279165	1995	19147	265652
1996	16487	247655	1996	24914	278409	1996	21241	263675	1996	17944	251537
1997	15511	237495	1997	23526	265231	1997	20030	251846	1997	16907	241000
1998	14305	221276	1998	21867	246095	1998	18564	233998	1998	15630	224410
1999	13120	210158	1999	20188	232187	1999	17095	221324	1999	14363	212955
2000	12136	199455	2000	18686	218800	2000	15812	209116	2000	13289	201926
2001	10999	190024	2001	17031	206680	2001	14377	198163	2001	12062	192162
2002	10239	187734	2002	15764	201796	2002	13325	194408	2002	11210	189559
2003	9735	190978	2003	14782	202369	2003	12545	196128	2003	10618	192466
2004	9477	194669	2004	14085	203234	2004	12033	198173	2004	10277	195754
2005	9422	195477	2005	13630	200981	2005	11746	197152	2005	10144	196060
2006	9590	196501	2006	13431	198668	2006	11701	196143	2006	10241	196484
2007	9973	198019	2007	13475	196514	2007	11887	195390	2007	10559	197295
2008	10560	202488	2008	13739	196923	2008	12287	197320	2008	11086	200944
2009	11339	206956	2009	14207	196911	2009	12886	198970	2009	11809	204482

Table 13. Estimates of the mid-year vulnerable biomass (mt) for 2009 from the four models and three fishery selectivities. Note that the vulnerable biomass is conditional on the selectivity, and assumes that a selectivity is applicable to the entire population. The values do not apply separately to each region.

	Model 1	Model 2	Model 3	Model 4
Differing assumptions:	σ estimated	σ =2.0	σ =2.5	σ =3.2
Differing data	CPUE by weight, integrated	CPUE by weight, integrated	CPUE by weight, integrated	CPUE by weight, integrated
Biomass removed using:				
Basin selectivity	4,894	4,406	4,562	4,801
NF Gulf selectivity	4,416	4,747	4,603	4,562
Shelf selectivity	5,093	4,747	4,856	5,030

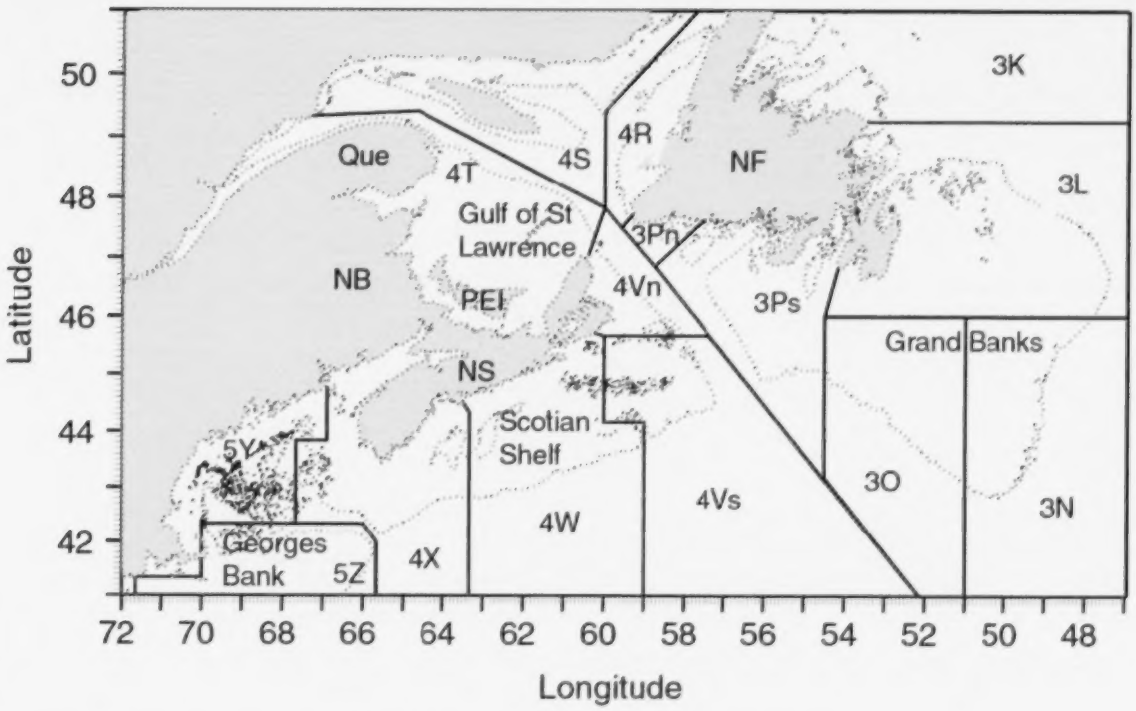


Figure 1. Map of eastern Canada showing NAFO Divisions and fishing banks.

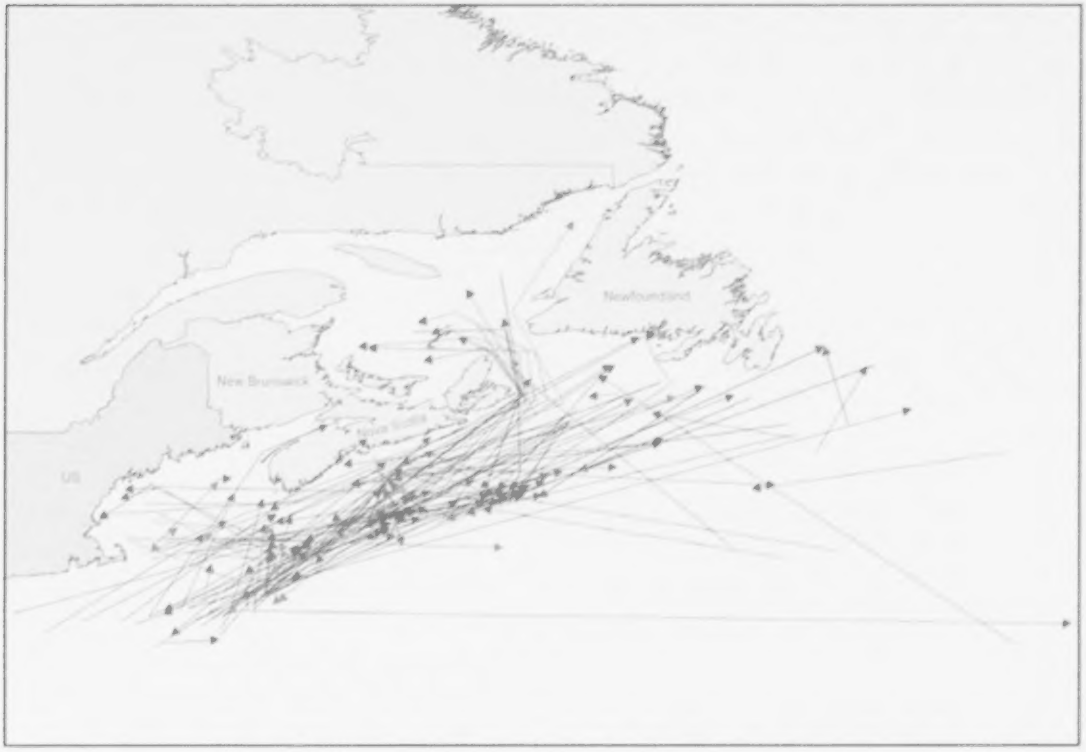
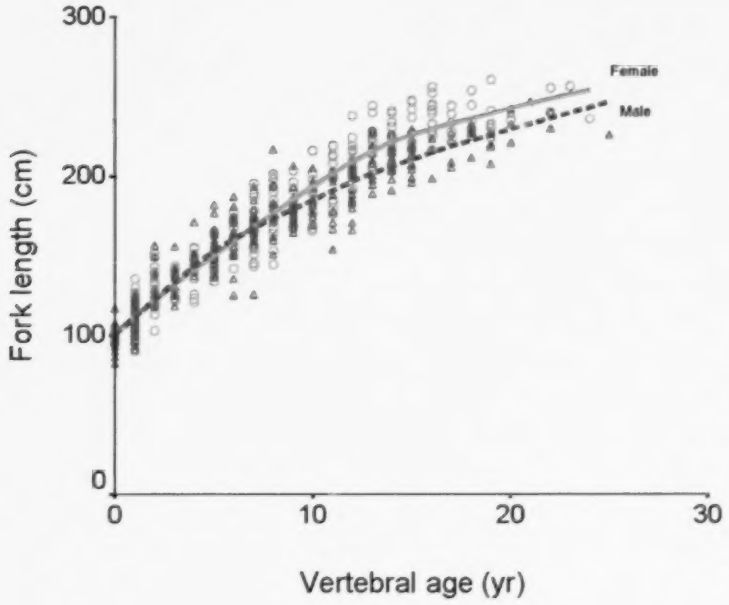


Figure 2. Summary of porbeagle tag movements from tagging location (line origin) to recapture location (arrowhead) between 1961 and 2008. Norwegian tags in green; U.S. tags in grey; Canadian tags in red.



Age	FL (cm)	Wt. At age (kg)
0	68	4.68
1	100	13.33
2	119	21.38
3	130	27.17
4	140	33.22
5	149	39.34
6	158	46.12
7	166	52.74
8	174	59.92
9	181	66.69
10	188	73.92
11	195	81.63
12	201	88.62
13	206	94.73
14	212	102.40
15	217	109.09
16	221	114.63
17	226	121.81
18	230	127.74
19	233	132.31
20	237	138.57

Von Bertalanffy growth model

$$L_t = L_\infty (1-e^{-K(t-t_0)})$$

	L_∞	K	t_0	N
Combined	289.4	0.066	-6.06	576
Male	257.7	0.080	-5.78	283
Female	309.8	0.061	-5.90	291

Figure 3. Growth curve for porbeagle shark, showing a reduction in growth rate for both sexes at the age of sexual maturity. Fitted lines are LOESS by sex. The age-length table is based on the von Bertalanffy growth model, substituting observed lengths for ages 0 and 1. Ages have been validated to age 11.

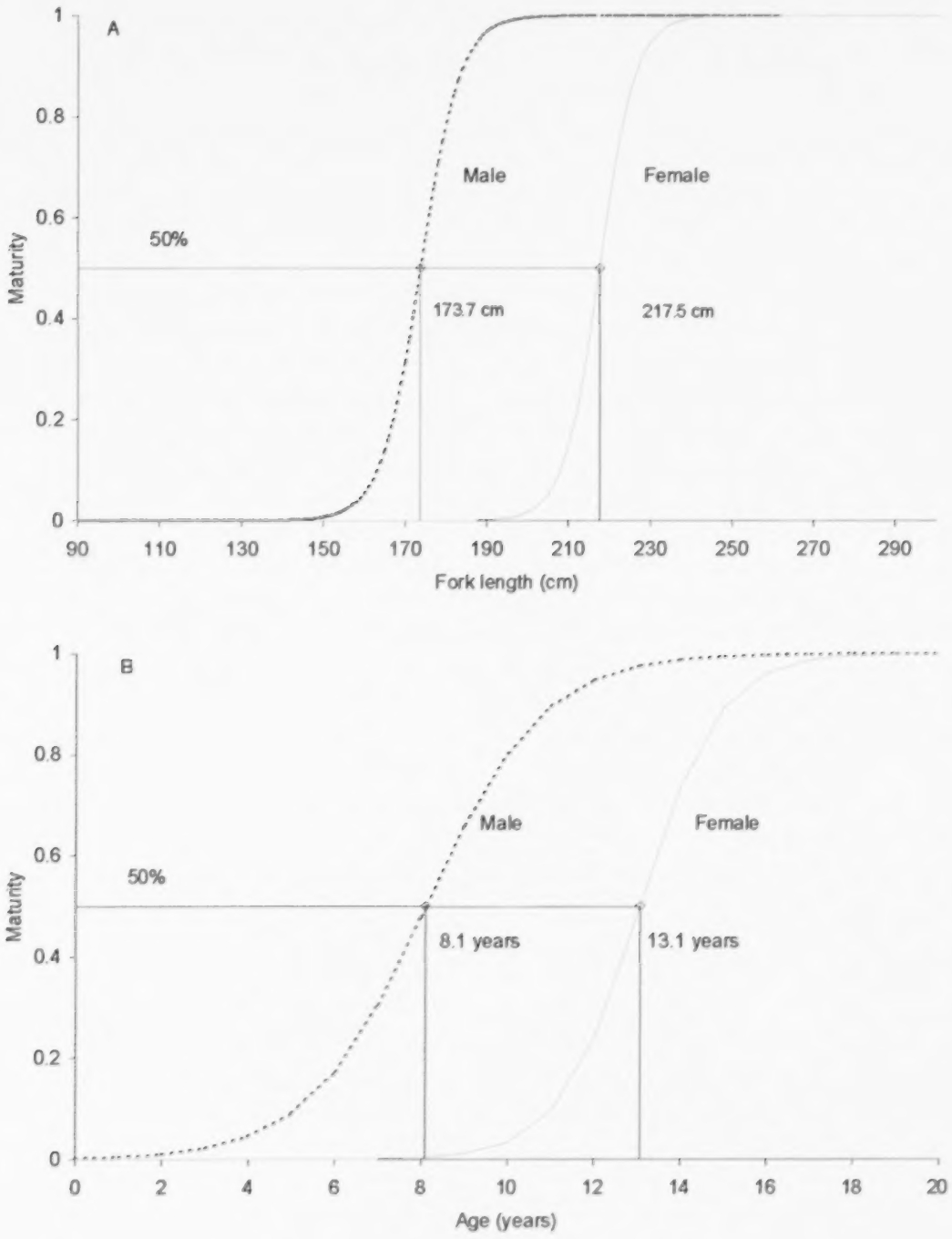


Figure 4. Maturity ogive for porbeagle shark, based on examination of 393 males and 382 females. Fitted lines are from logistic regression.

Figure 5. Known mating grounds for porbeagle shark in the NW Atlantic (ovals). Symbols shown capture locations for pregnant females.

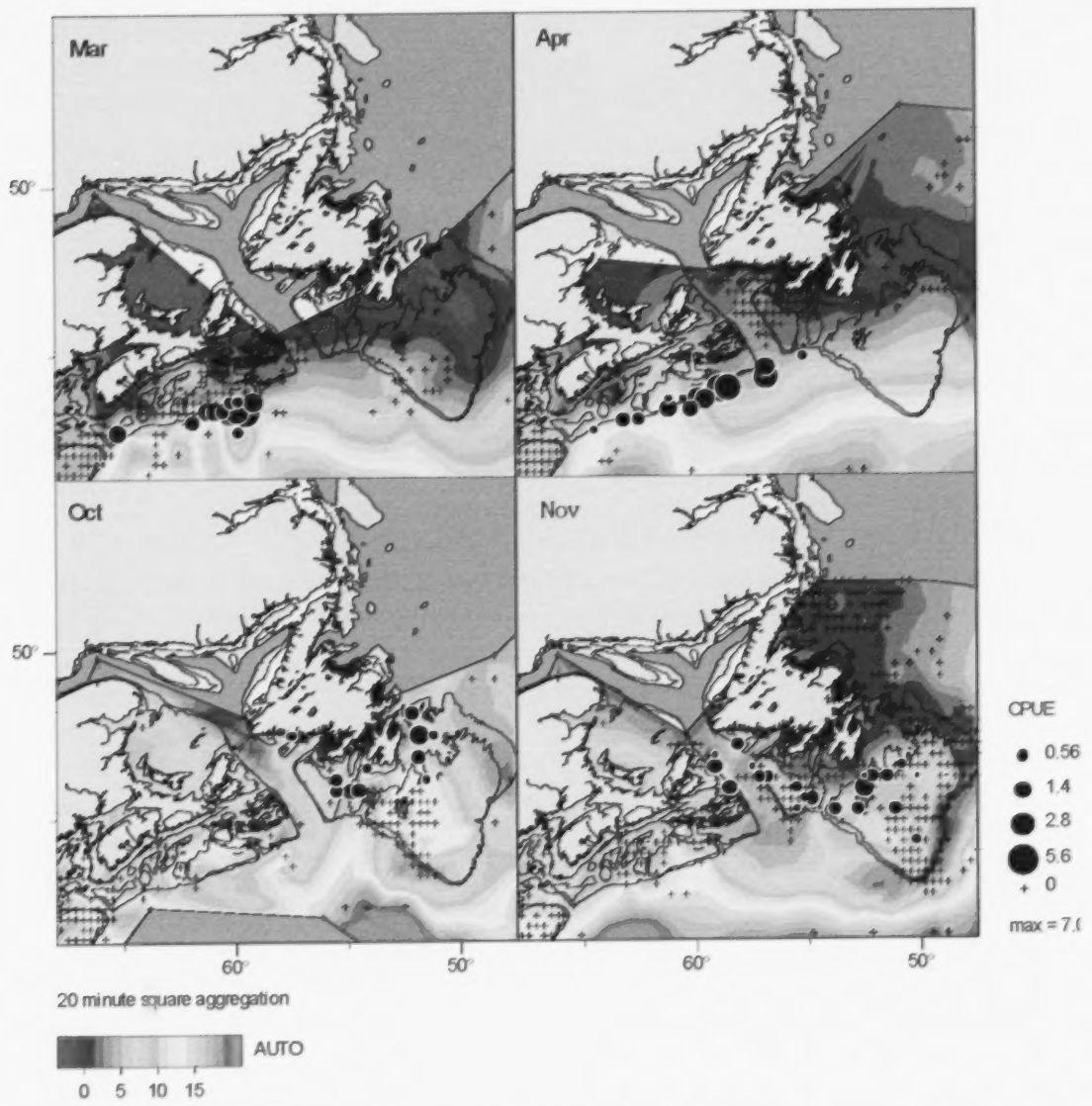


Figure 6. Porbeagle catch and associated temperature at mid-gear depth for 1999 (from Campana and Joyce (2004).

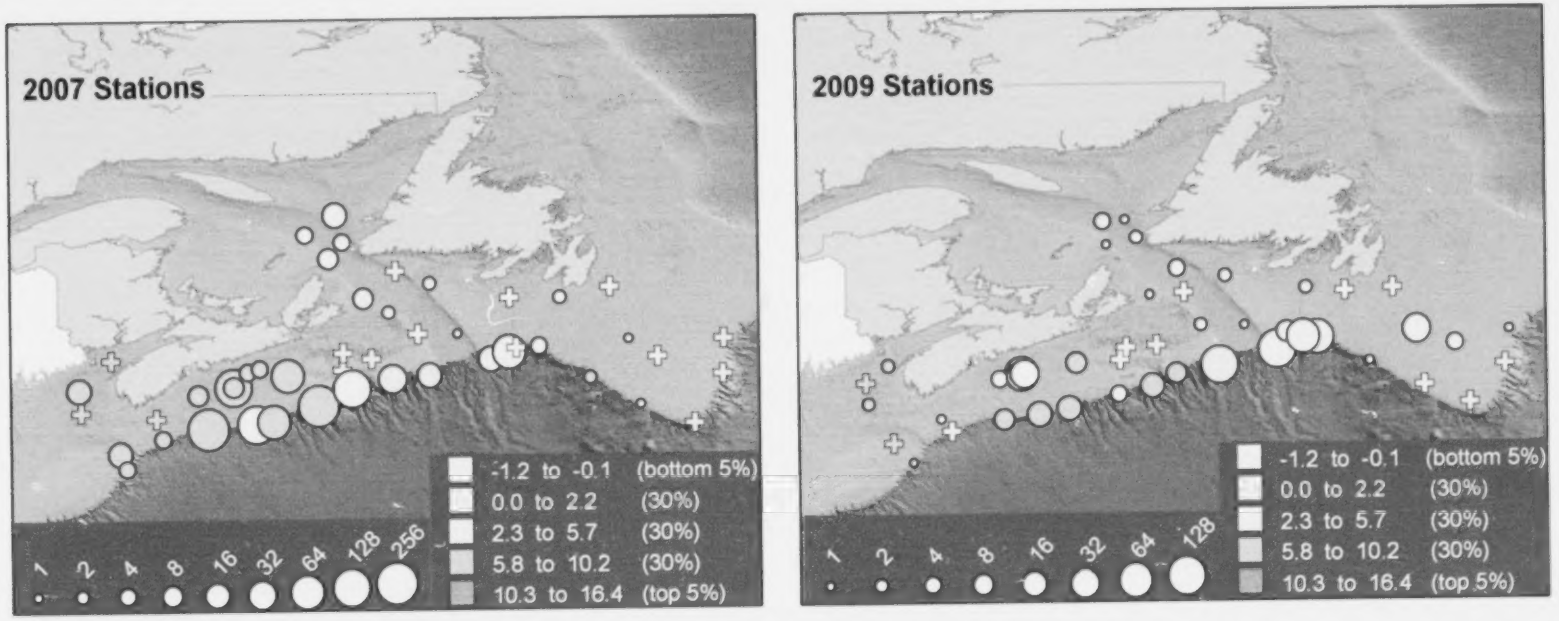


Figure 7. A comparison of porbeagle survey abundance in 2007 and in 2009. Circles indicate porbeagle catch where crosses indicate nulls. Catch abundance per survey station is represented by a graduated symbology, whereas average temperature at the depth of the gear is represented by a colour ramp.

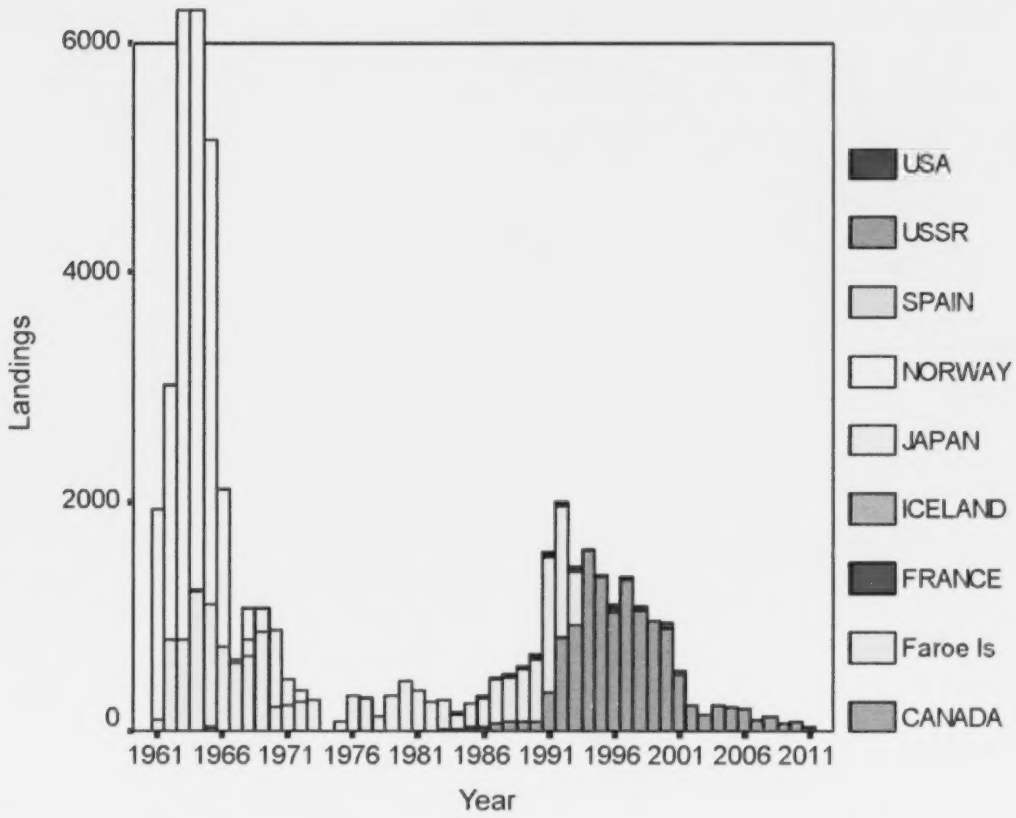


Figure 8. Porbeagle landings in northwest Atlantic (NAFO 2-6) from 1961 to 2011.

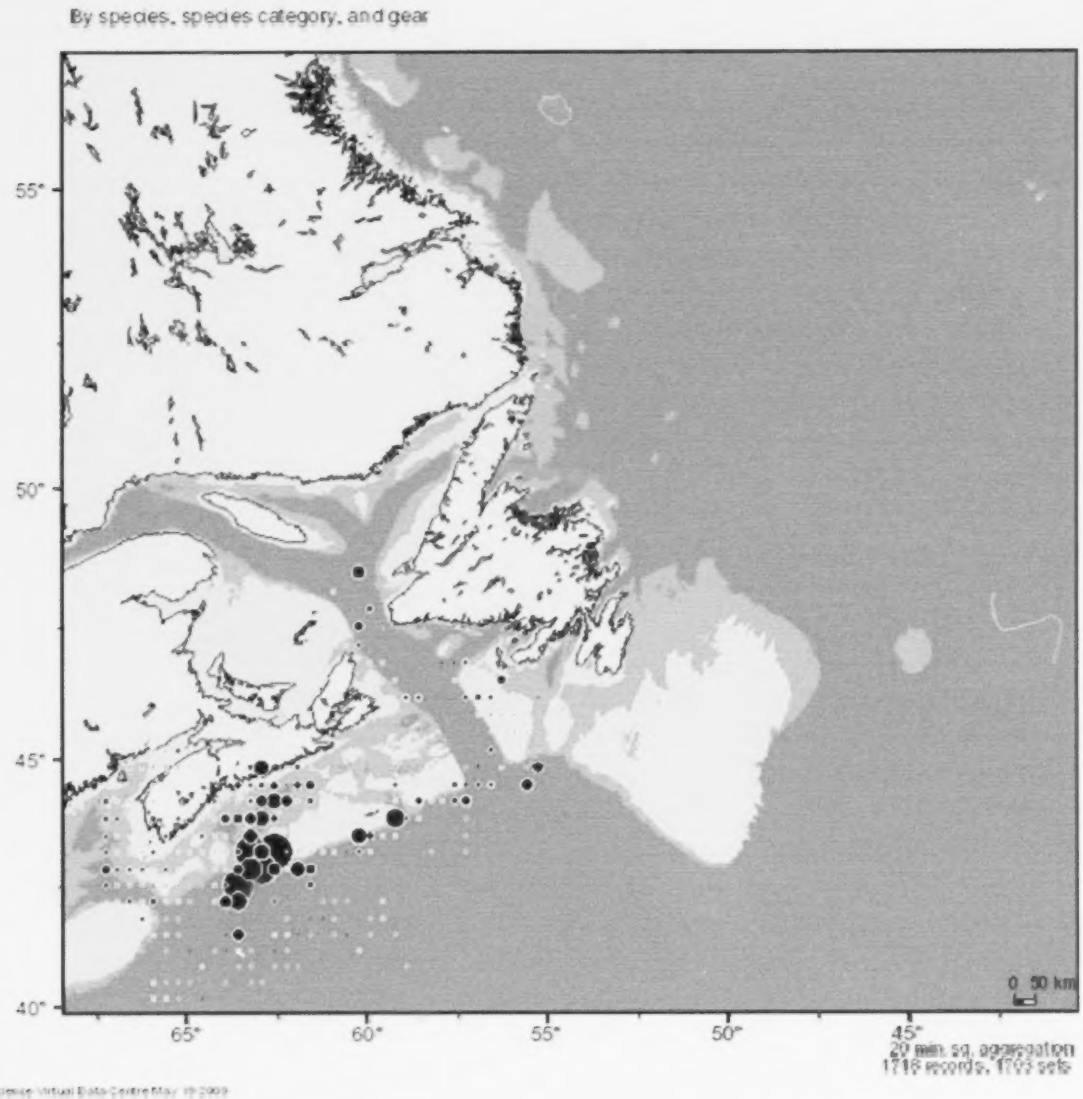


Figure 9. Porbeagle catch locations 2005-2008.

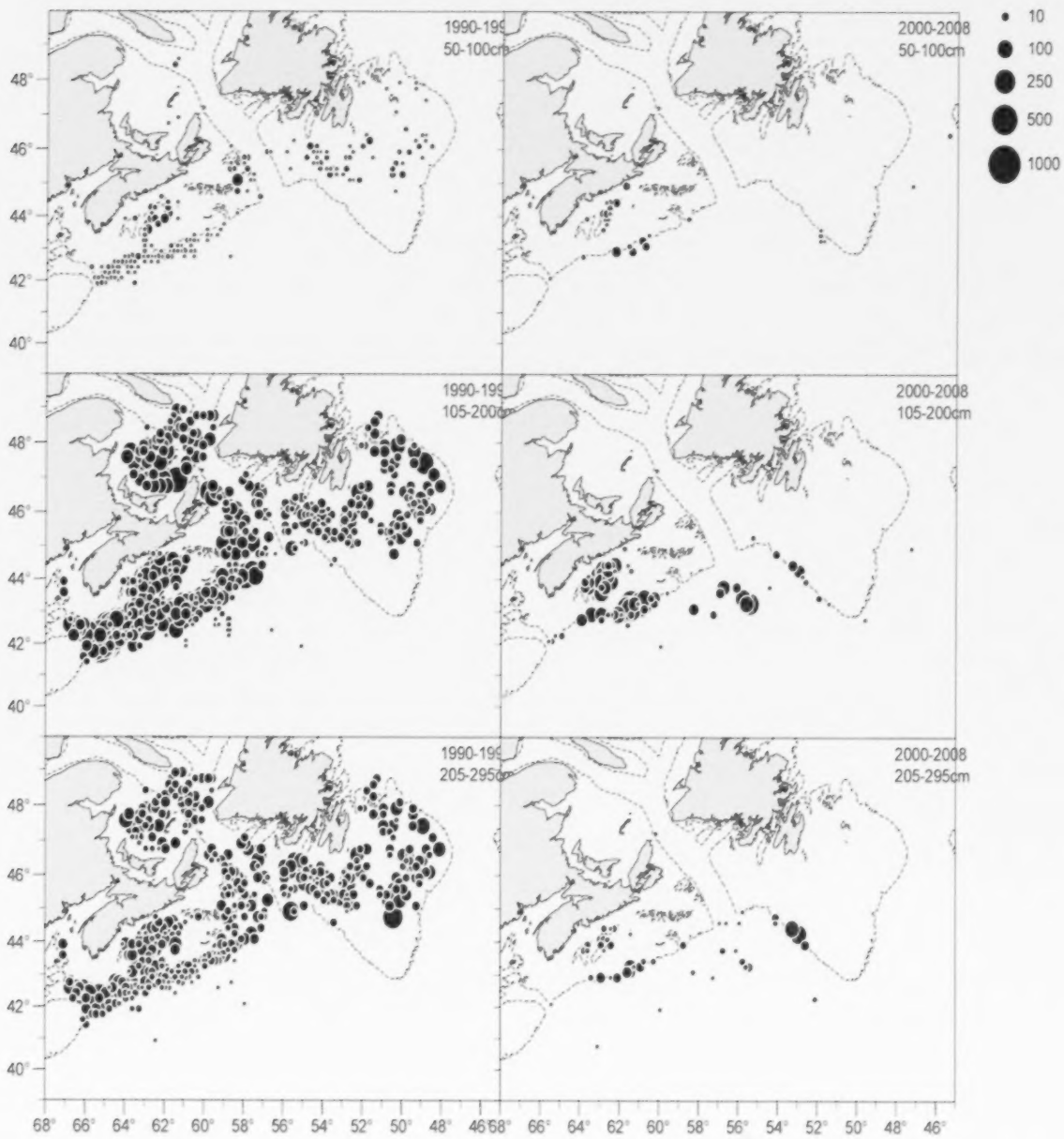


Figure 10. Young of the year, juvenile and adult porbeagle distribution by decade as observed by the DFO Observer Program.

Figure 11. Porbeagle distribution by life history stage as observed by the U.S. Pelagic Observer Program and the U.S. Cooperative Tagging Program between 2000 and 2007. Map and data from NMFS (2008) and 2008. (Continued below.)

Figure 11. Continued.

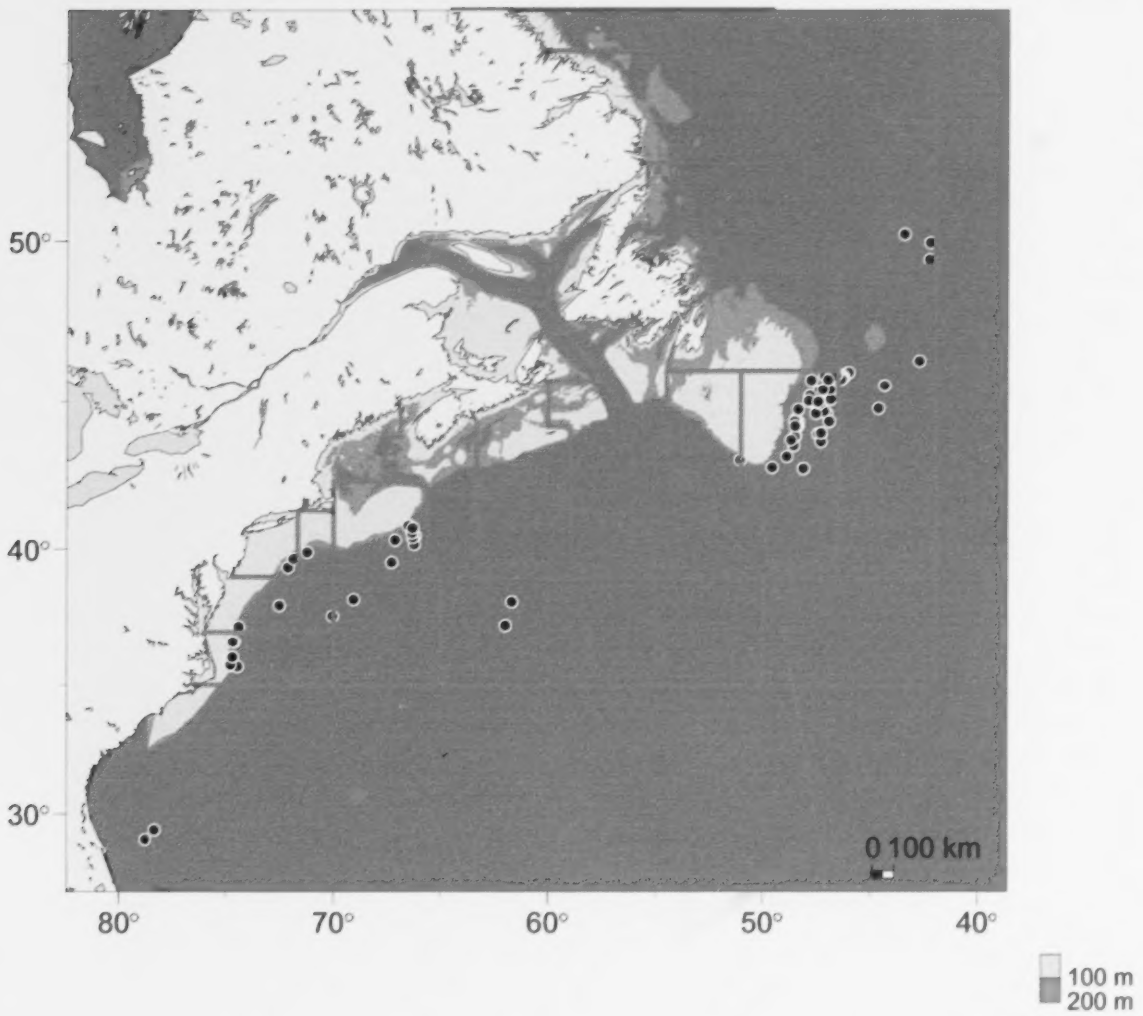


Figure 12. Juvenile (FL<120 cm) porbeagle distribution as observed by the U.S. Pelagic Observer Program between 2000 and 2007. Data courtesy of Enric Cortés, NMFS.

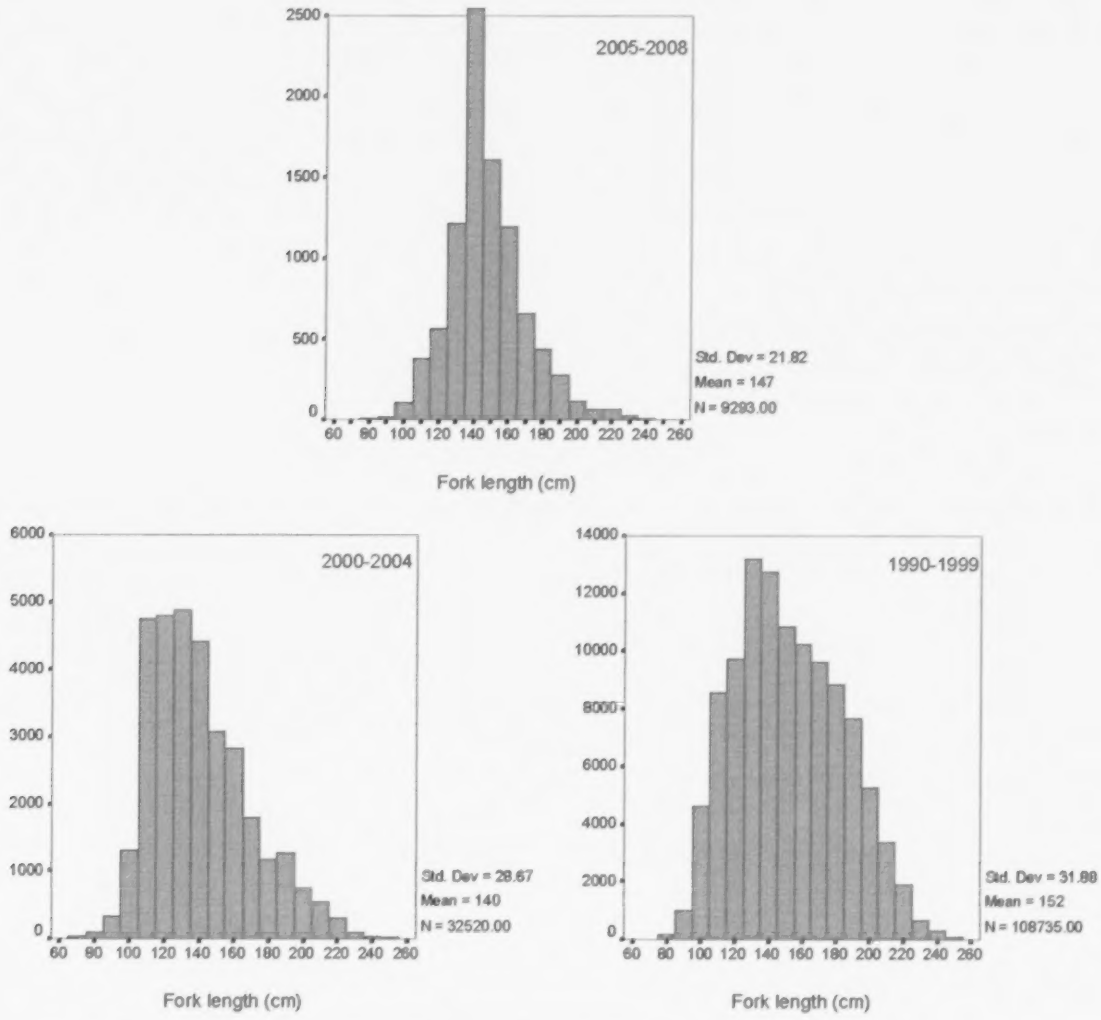


Figure 13. Porbeagle length frequencies in commercial catch.

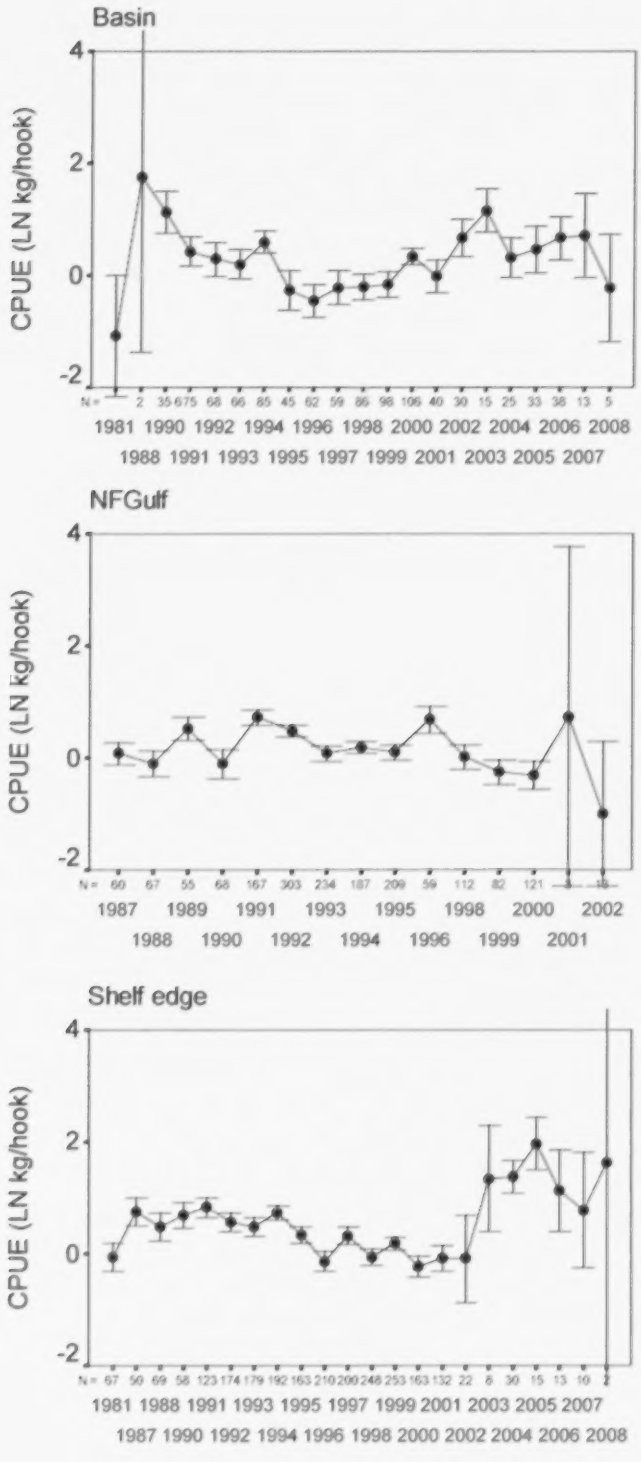


Fig 14a. Error bar plots (mean and 95% CI) showing porbeagle CPUE by area in terms of ln-transformed kg/hook. Note that the years differ between the graphs.

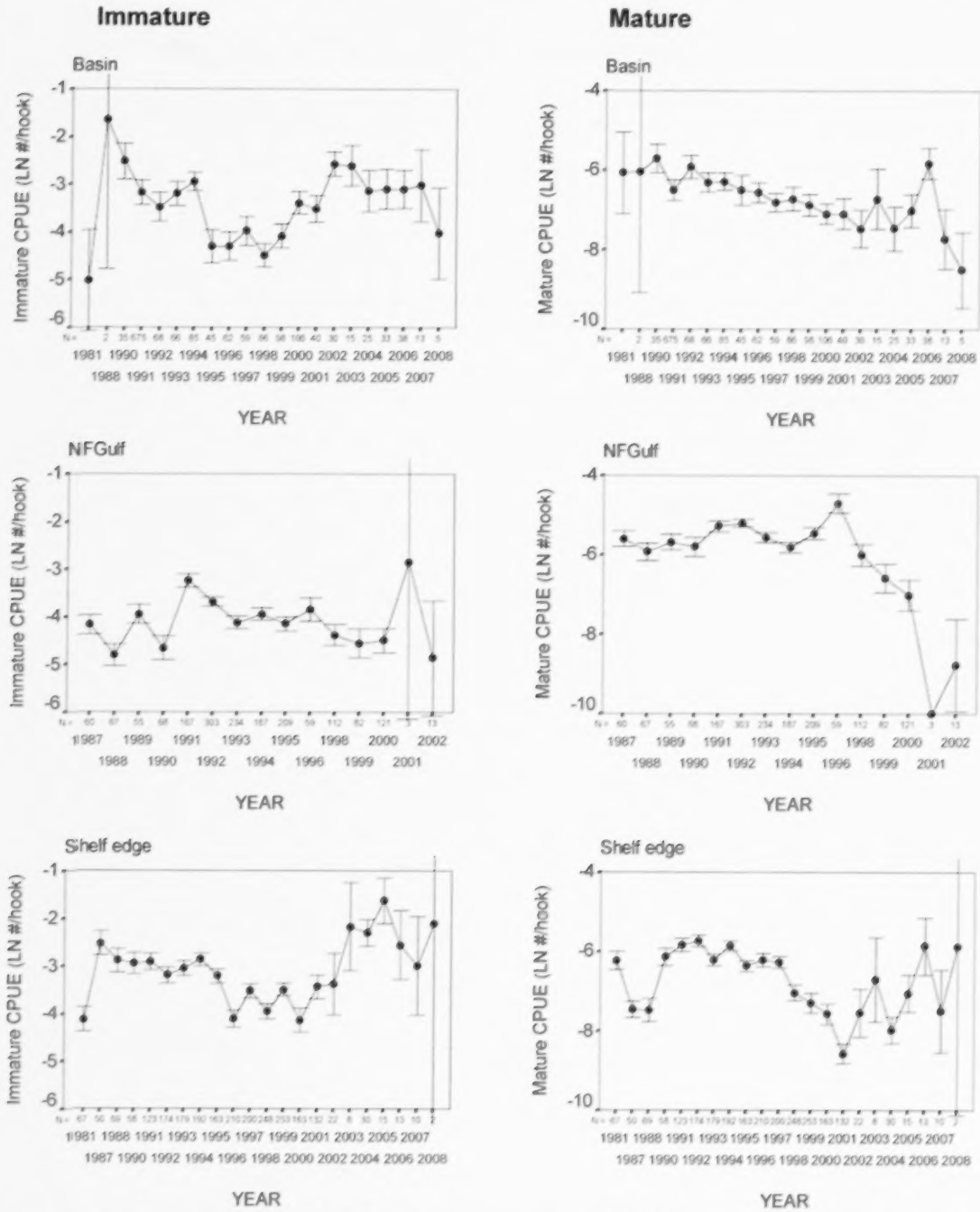


Figure 14b. Error bar plots (mean and 95% CI) showing porbeagle CPUE by area and maturity stage in terms of ln-transformed number/hook. Note that the years differ between the graphs.

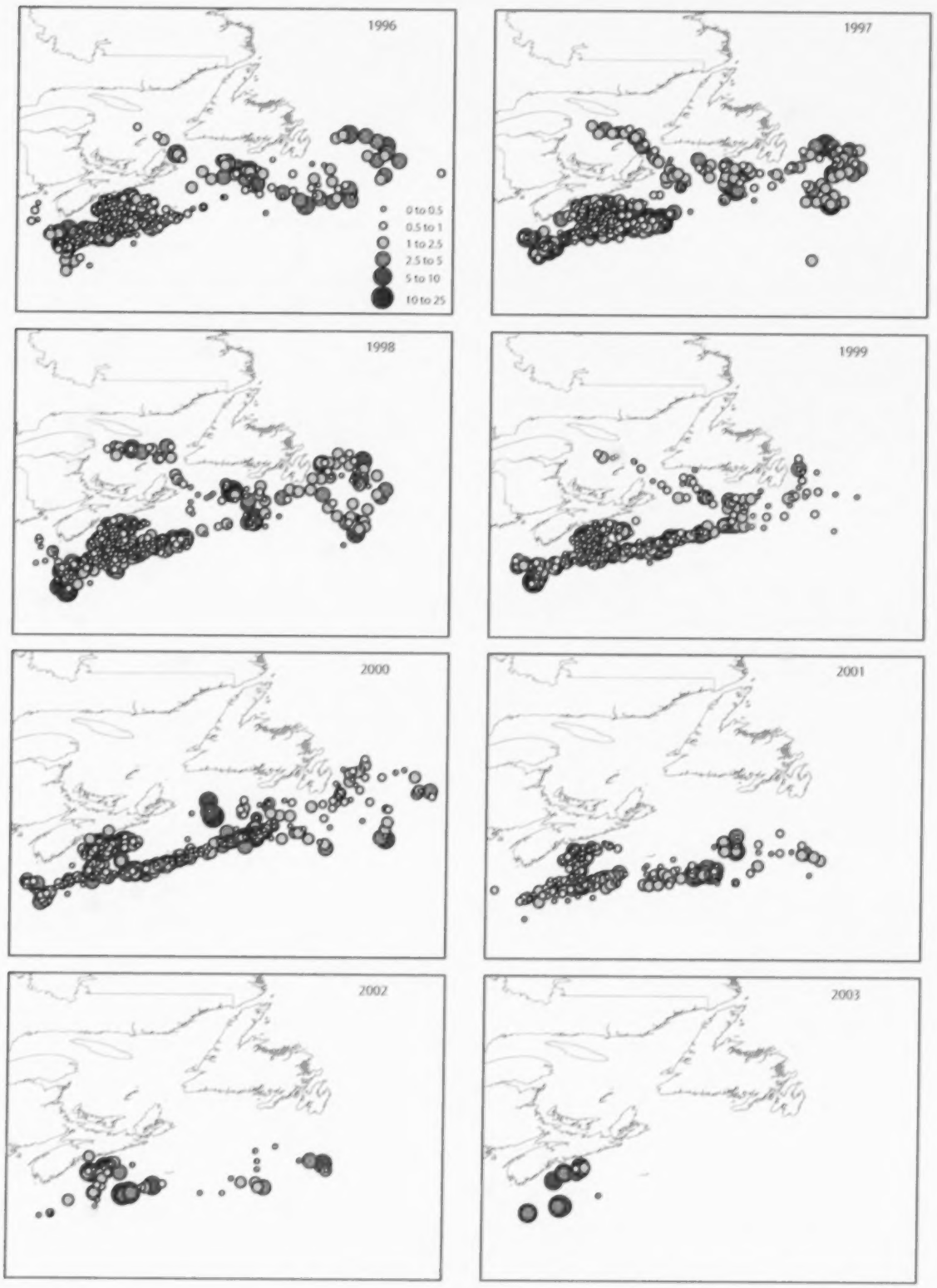


Figure 15. Distribution of porbeagle CPUE by year, 1996-2008 (continued below).

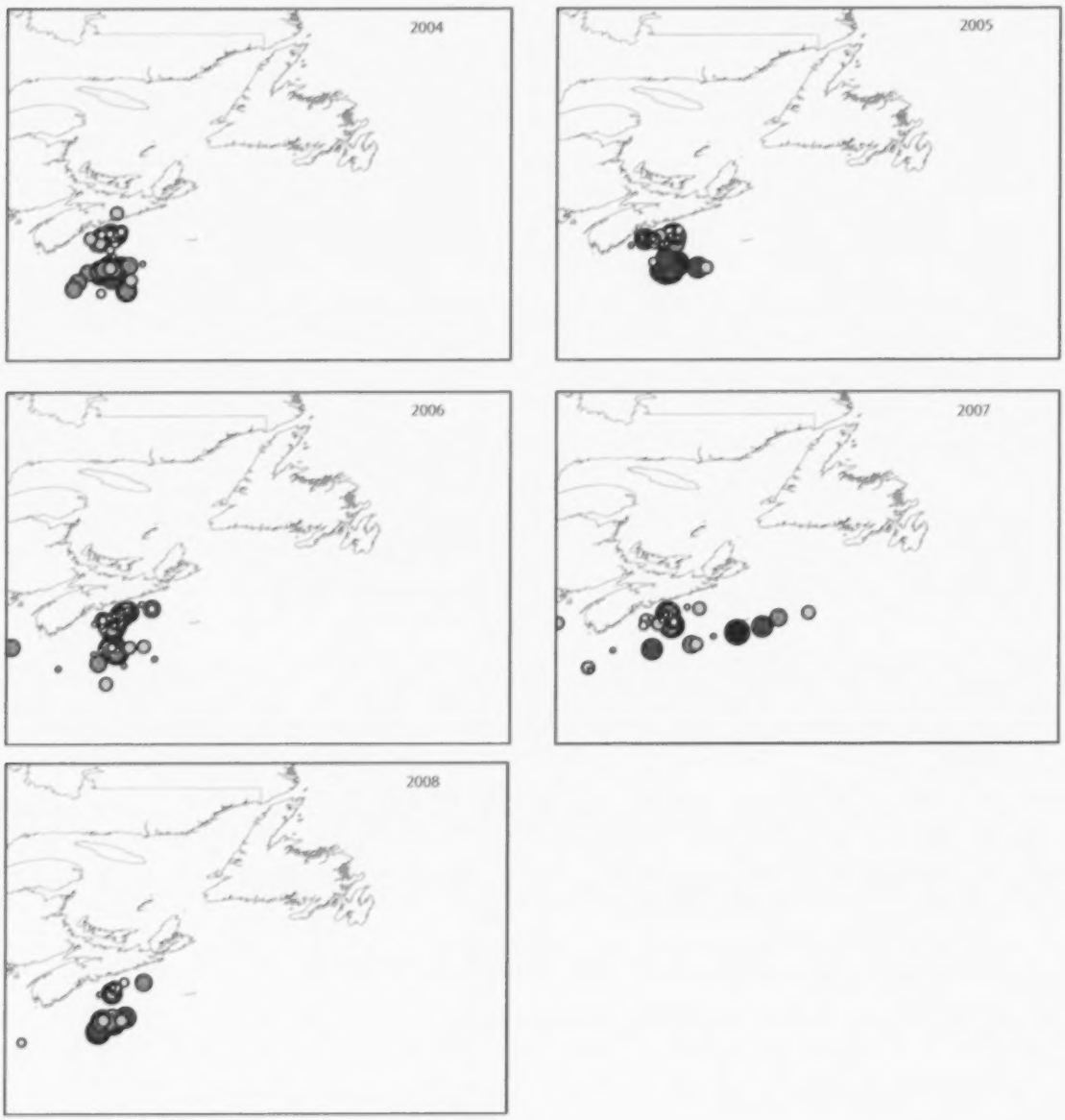


Figure 15. Continued.

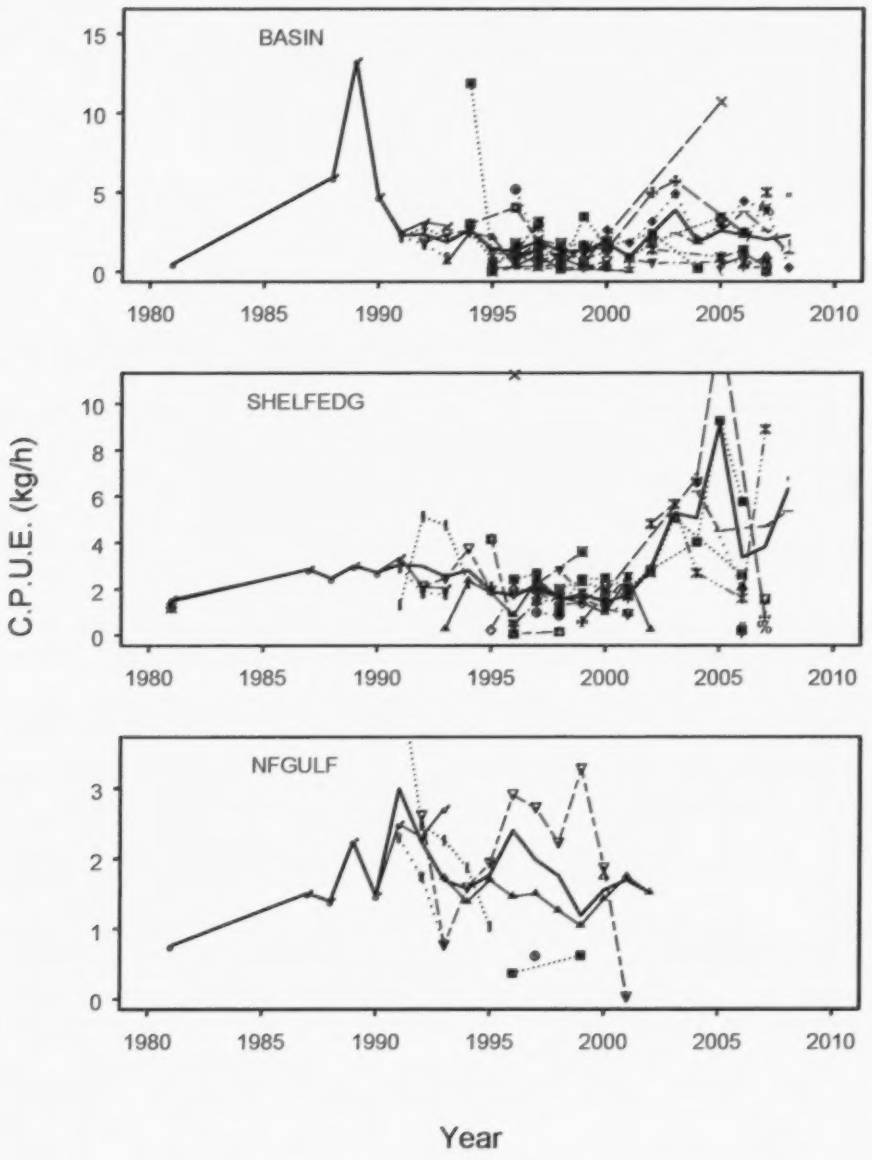


Figure 16. Comparison of the grand mean of the CPUE (kg/hook) with the mean CPUE for each vessel.

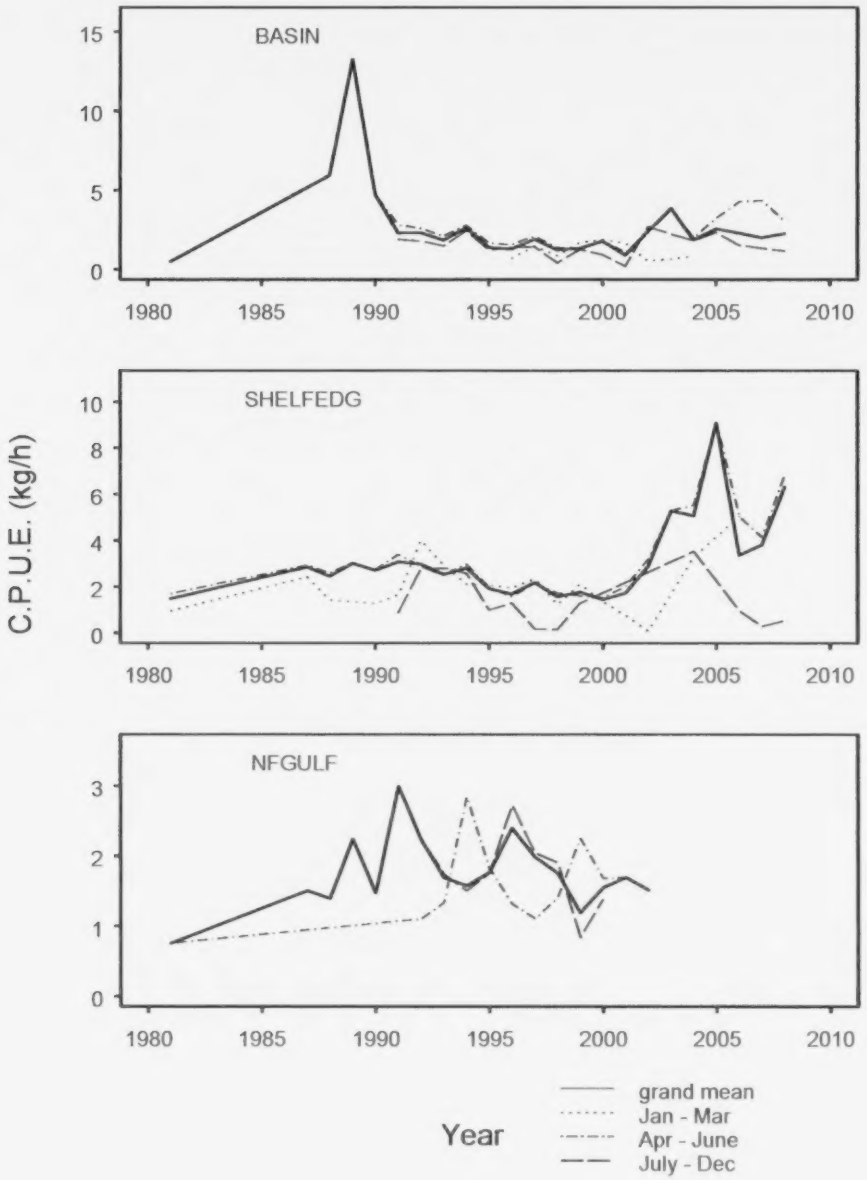


Figure 17. Comparison of the grand mean of the CPUE (kg/hook) with the seasonal mean CPUEs.

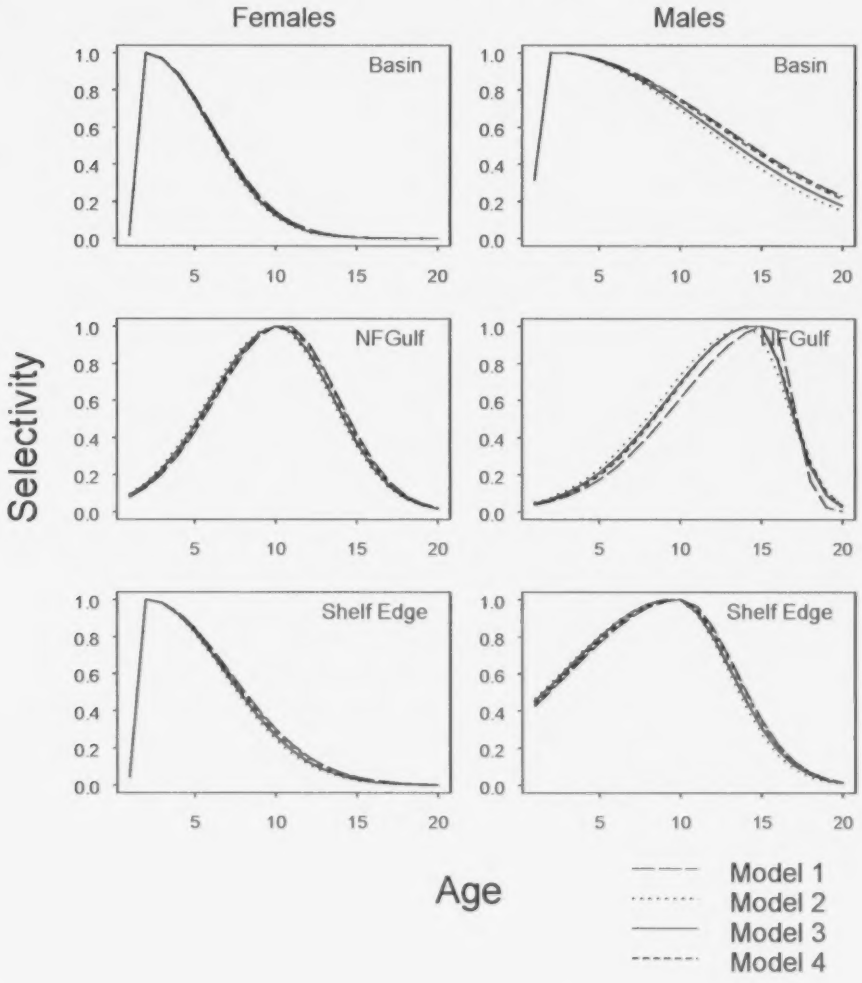


Figure 18. Estimated selectivity curves for porbeagle fisheries in three regions obtained from the four models (see text).

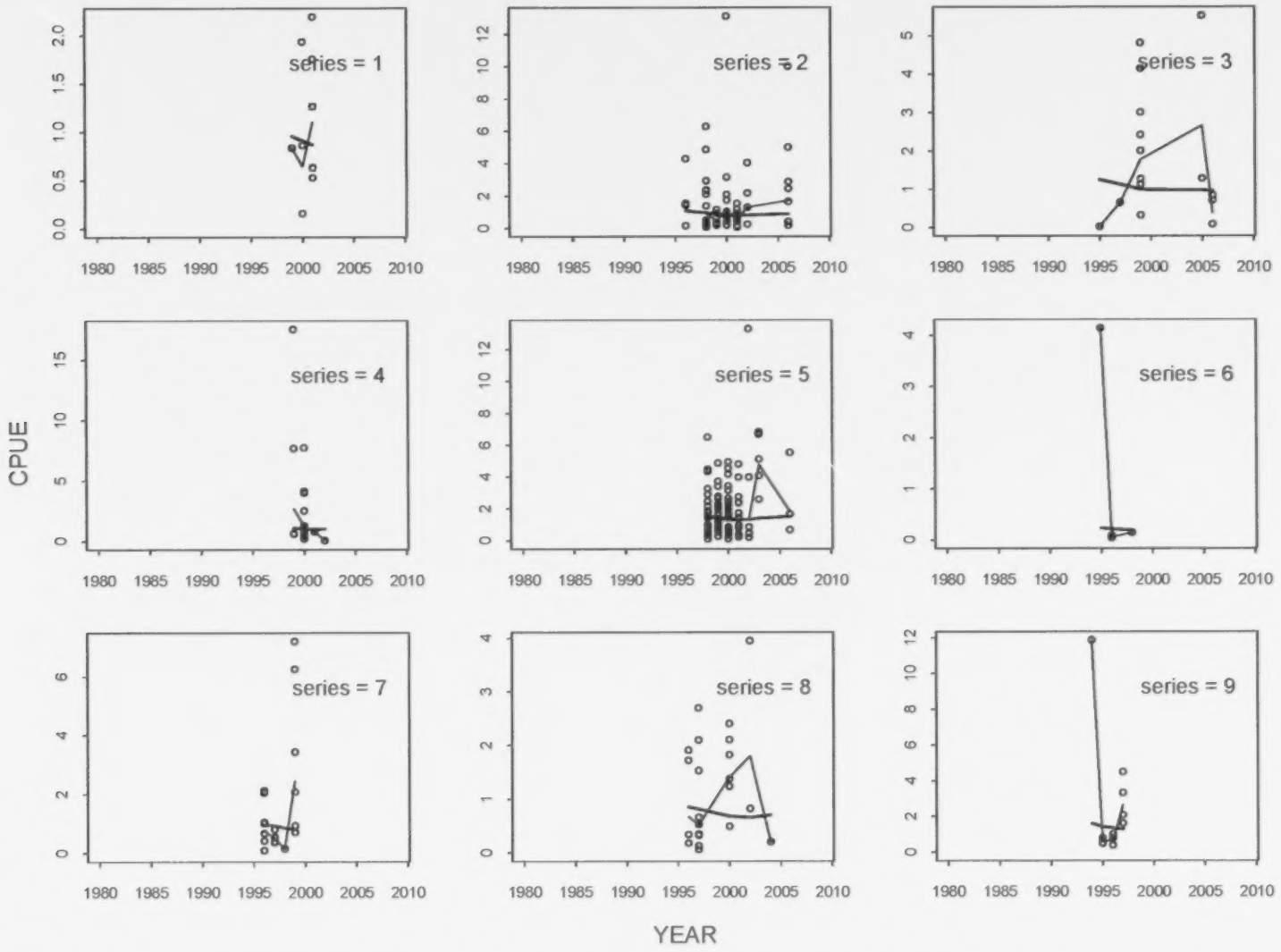


Figure 19.1. Observed (points) and fitted (lines) catch per unit effort by weight for each porbeagle CPUE series (a single vessel fishing in a single area during a single season). The light line is the annual geometric mean of the data. The dark line is the model fit obtained from Model 3.

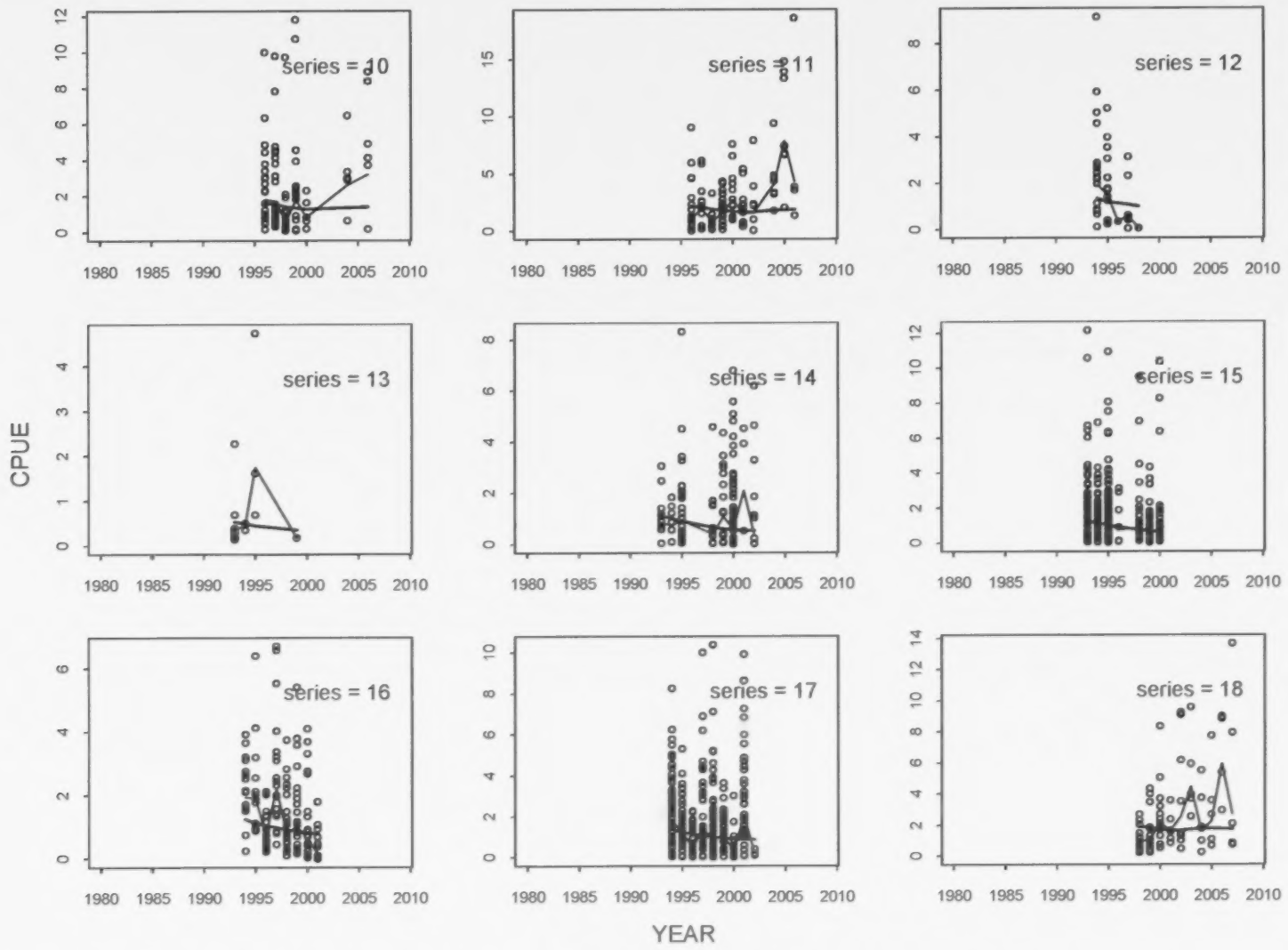


Figure 19.2. Observed (points) and fitted (lines) catch per unit effort by weight for each porbeagle CPUE series (a single vessel fishing in a single area during a single season). The light line is the annual geometric mean of the data. The dark line is the model fit obtained from Model 3.

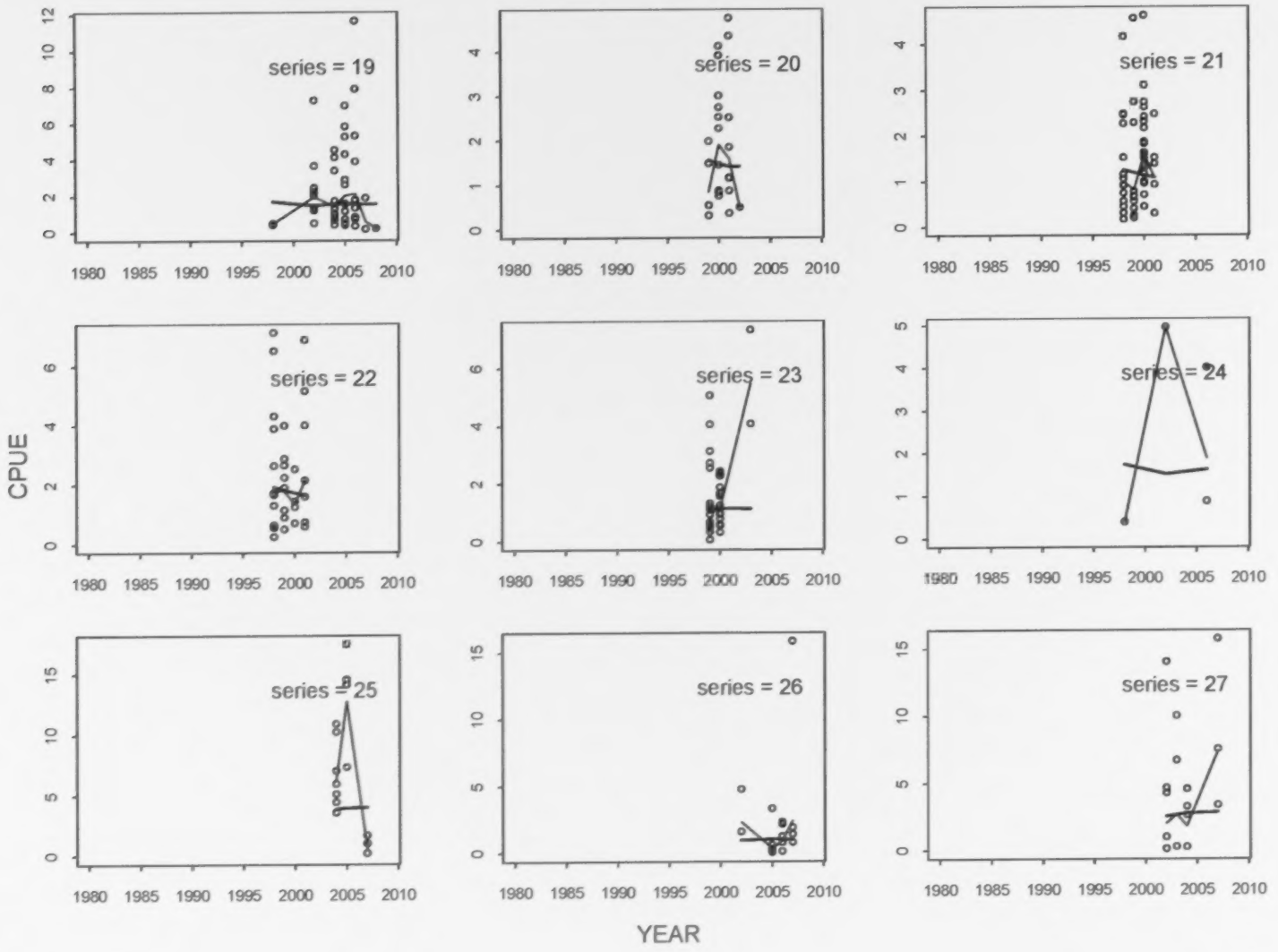


Figure 19.3. Observed (points) and fitted (lines) catch per unit effort by weight for each porbeagle CPUE series (a single vessel fishing in a single area during a single season). The light line is the annual geometric mean of the data. The dark line is the model fit obtained from Model 3.

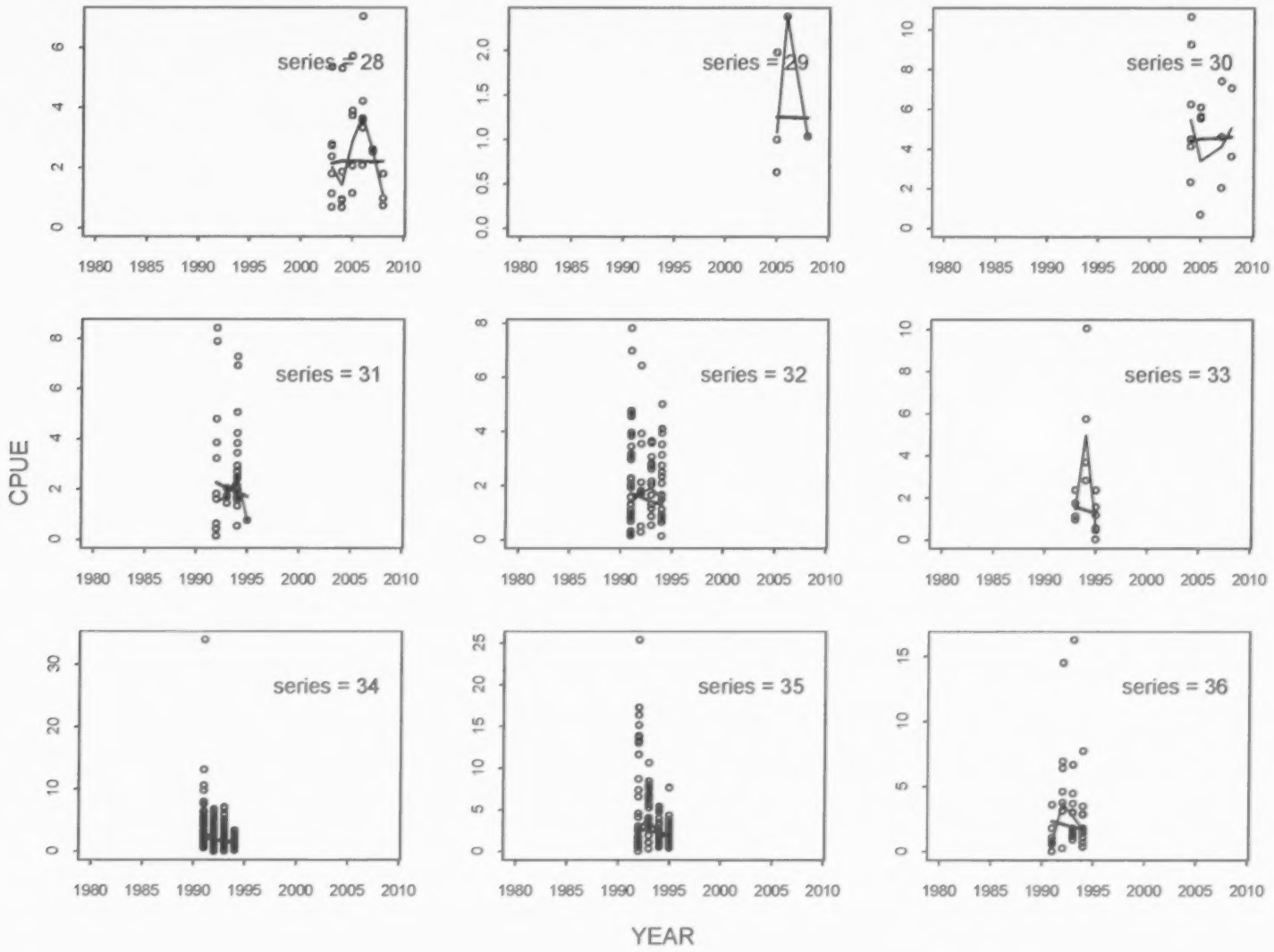


Figure 19.4. Observed (points) and fitted (lines) catch per unit effort by weight for each porbeagle CPUE series (a single vessel fishing in a single area during a single season). The light line is the annual geometric mean of the data. The dark line is the model fit obtained from Model 3.

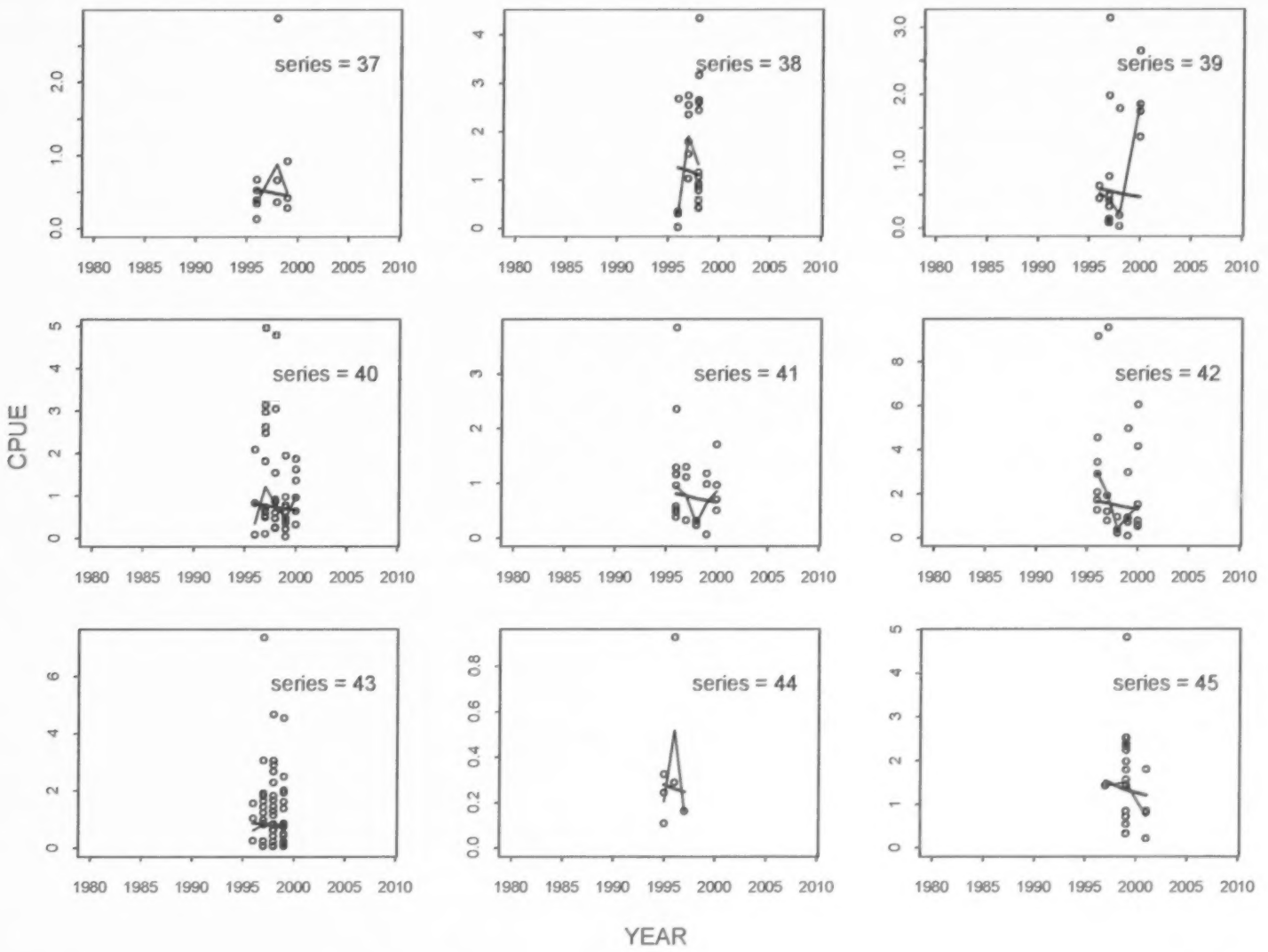


Figure 19.5. Observed (points) and fitted (lines) catch per unit effort by weight for each porbeagle CPUE series (a single vessel fishing in a single area during a single season). The light line is the annual geometric mean of the data. The dark line is the model fit obtained from Model 3.

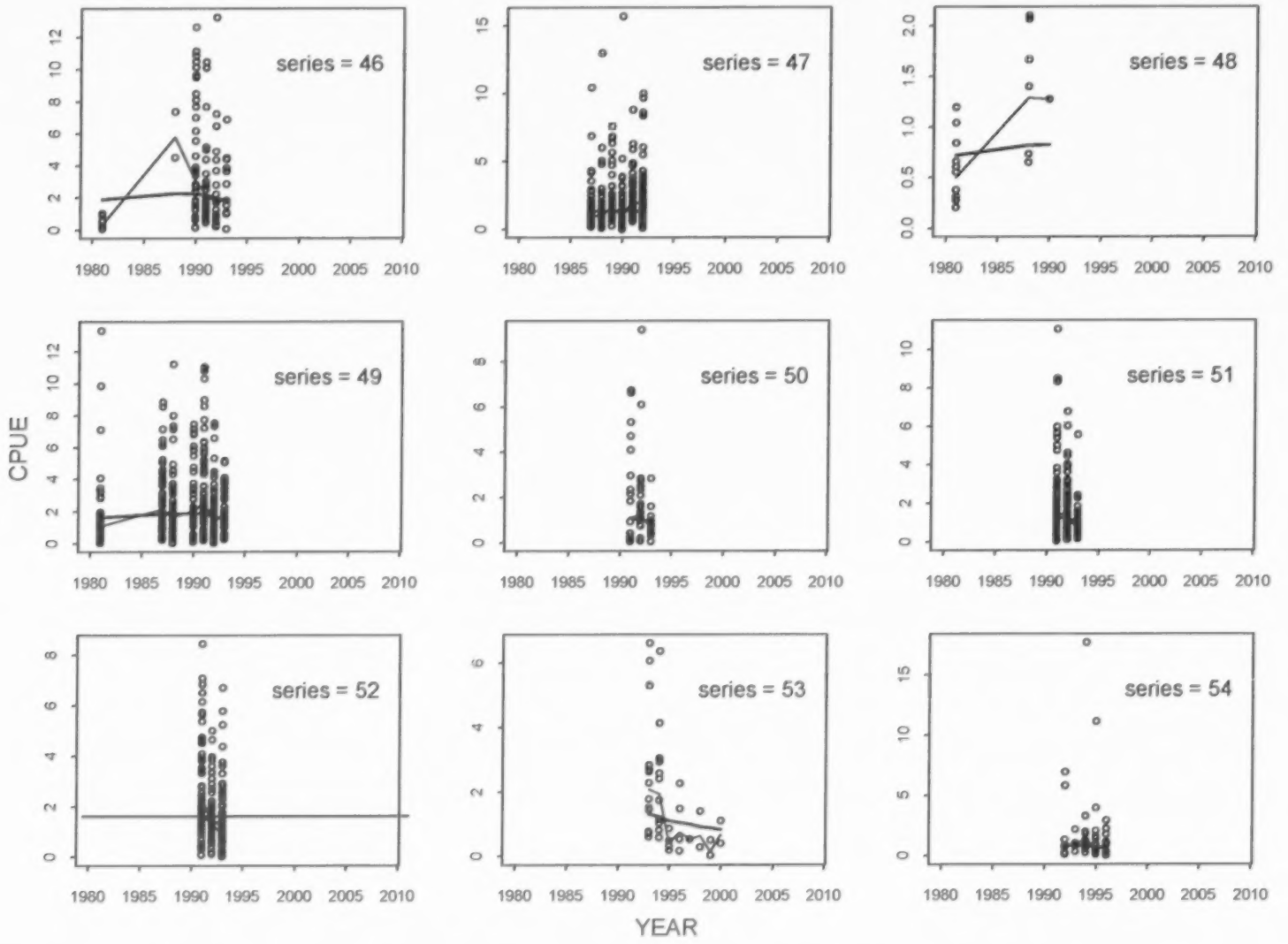


Figure 19.6. Observed (points) and fitted (lines) catch per unit effort by weight for each porbeagle CPUE series (a single vessel fishing in a single area during a single season). The light line is the annual geometric mean of the data. The dark line is the model fit obtained from Model 3.

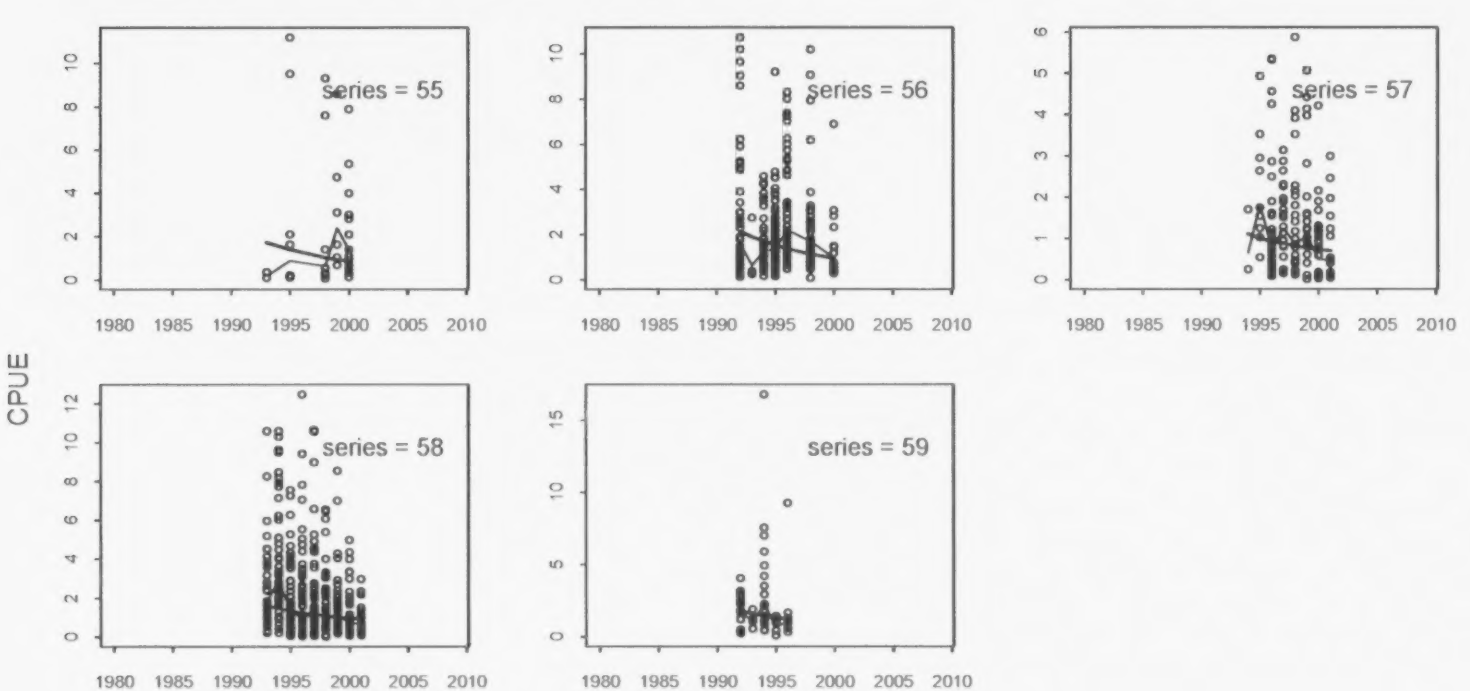


Figure 19.7. Observed (points) and fitted (lines) catch per unit effort by weight for each porbeagle CPUE series (a single vessel fishing in a single area during a single season). The light line is the annual geometric mean of the data. The dark line is the model fit obtained from Model 3.

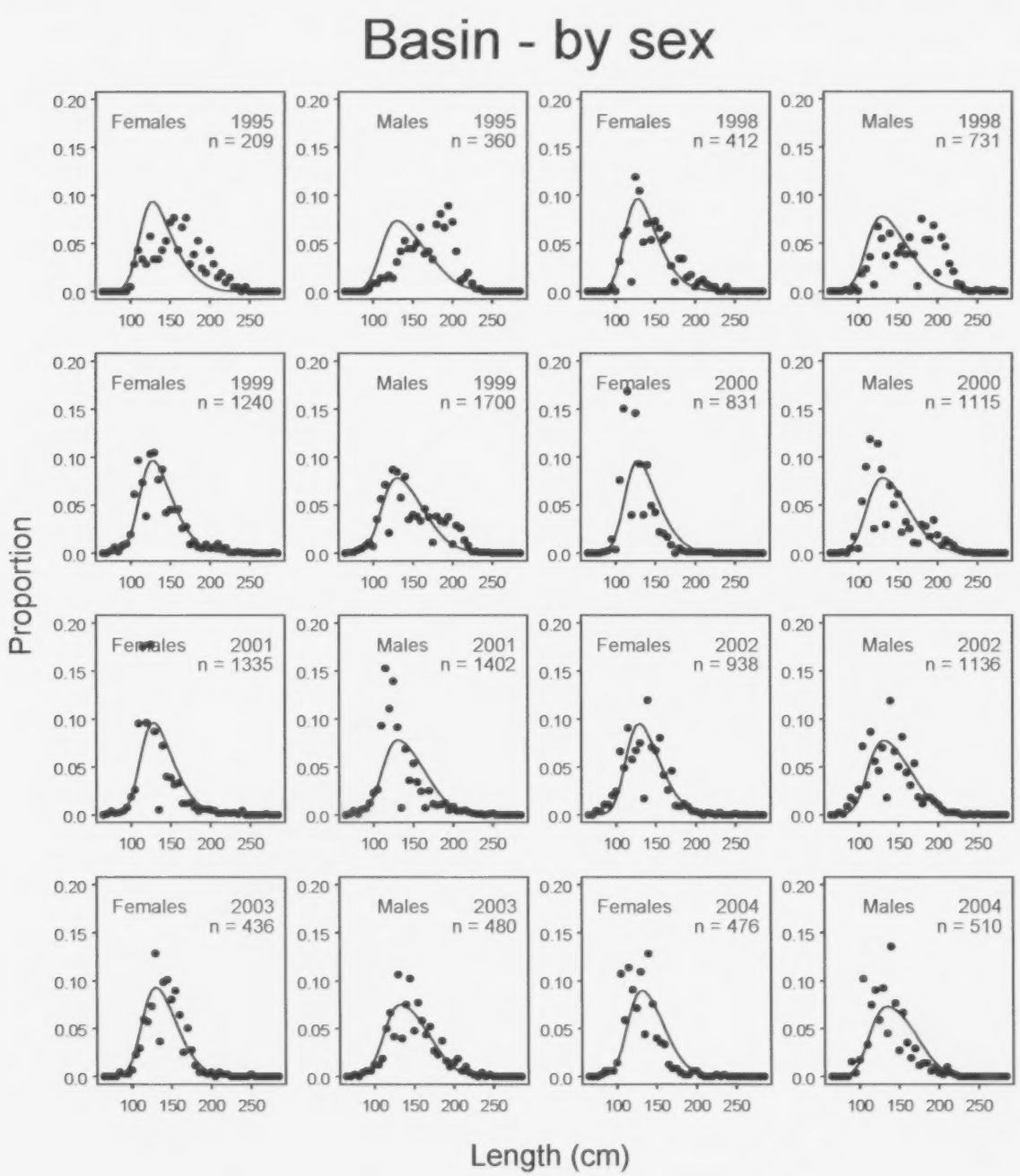


Figure 20.1. Observed (points) and fitted (lines) catch-at-length proportions by sex in the Basin region. Line symbolism is the same as Figure 19. All fits are virtually identical (continued below).

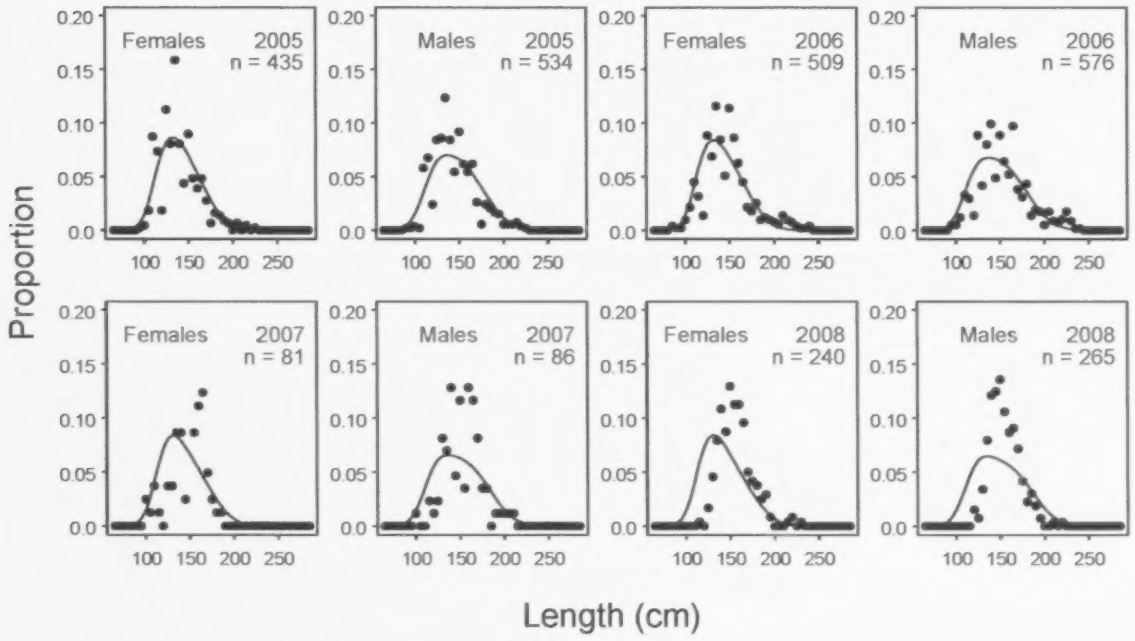


Figure 20.1. Continued.

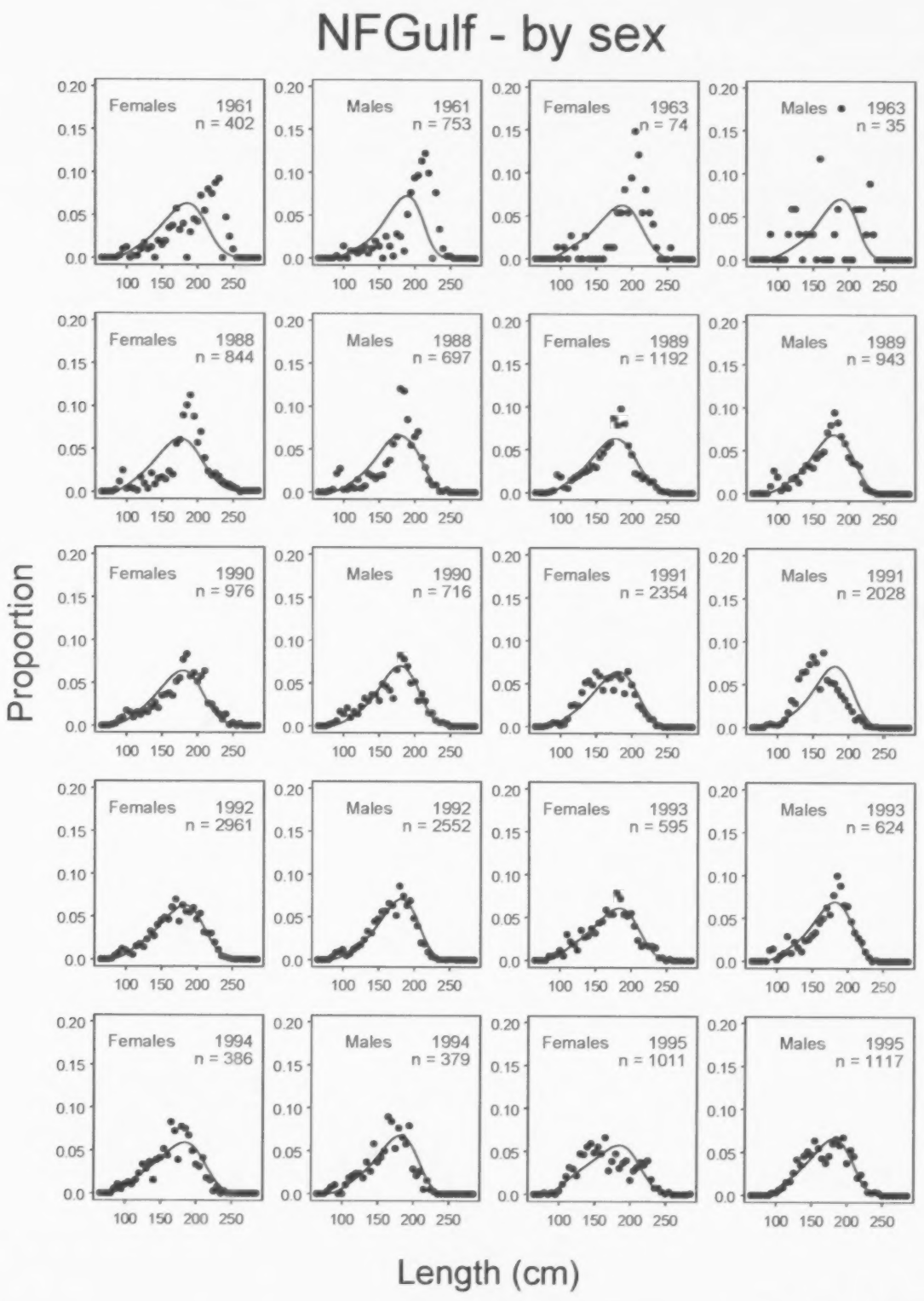


Figure 20.2. Observed (points) and fitted (lines) catch-at-length proportions by sex in the NF-Gulf region up to 1995. Line symbolism is the same as Figure 19. All fits are virtually identical.

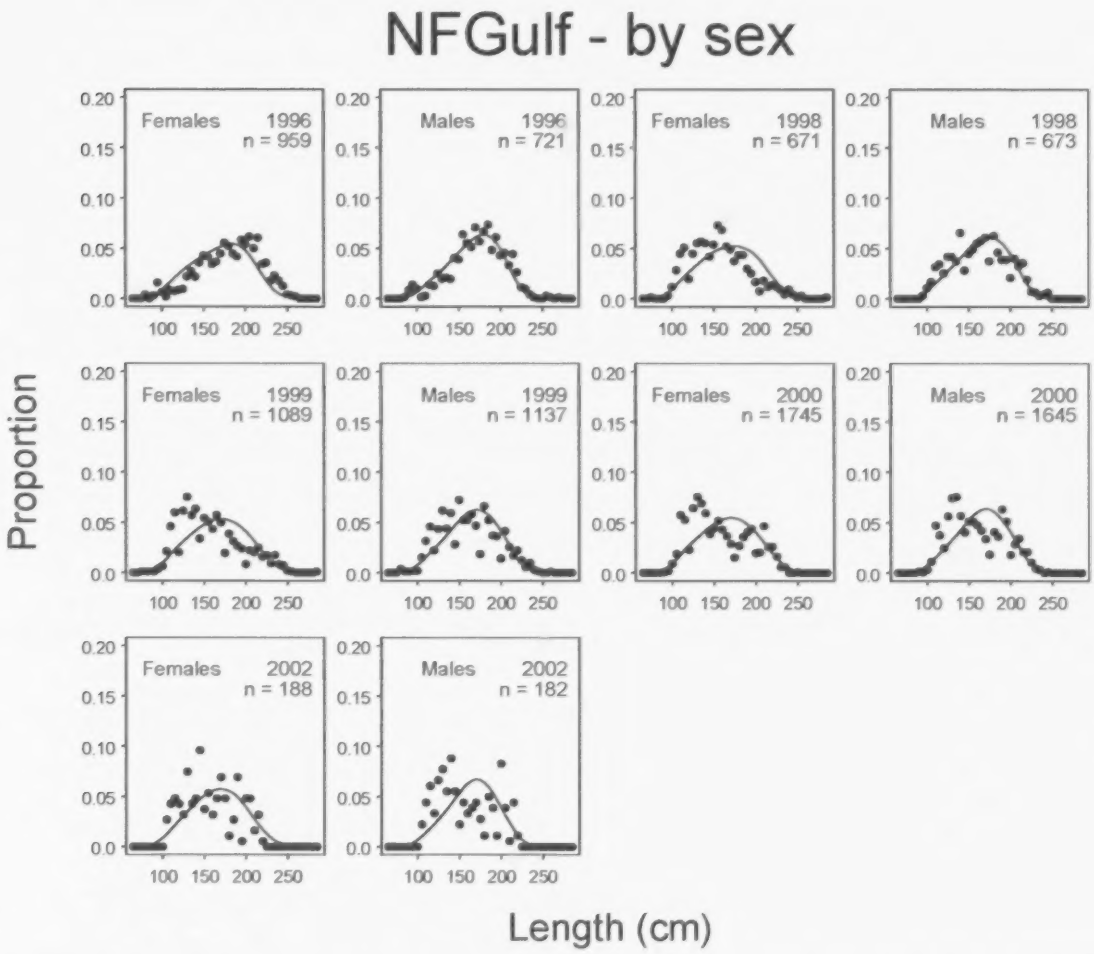


Figure 20.3. Observed (points) and fitted (lines) catch-at-length proportions by sex in the NF-Gulf region after 1996. Line symbolism is the same as Figure 19. All fits are virtually identical.

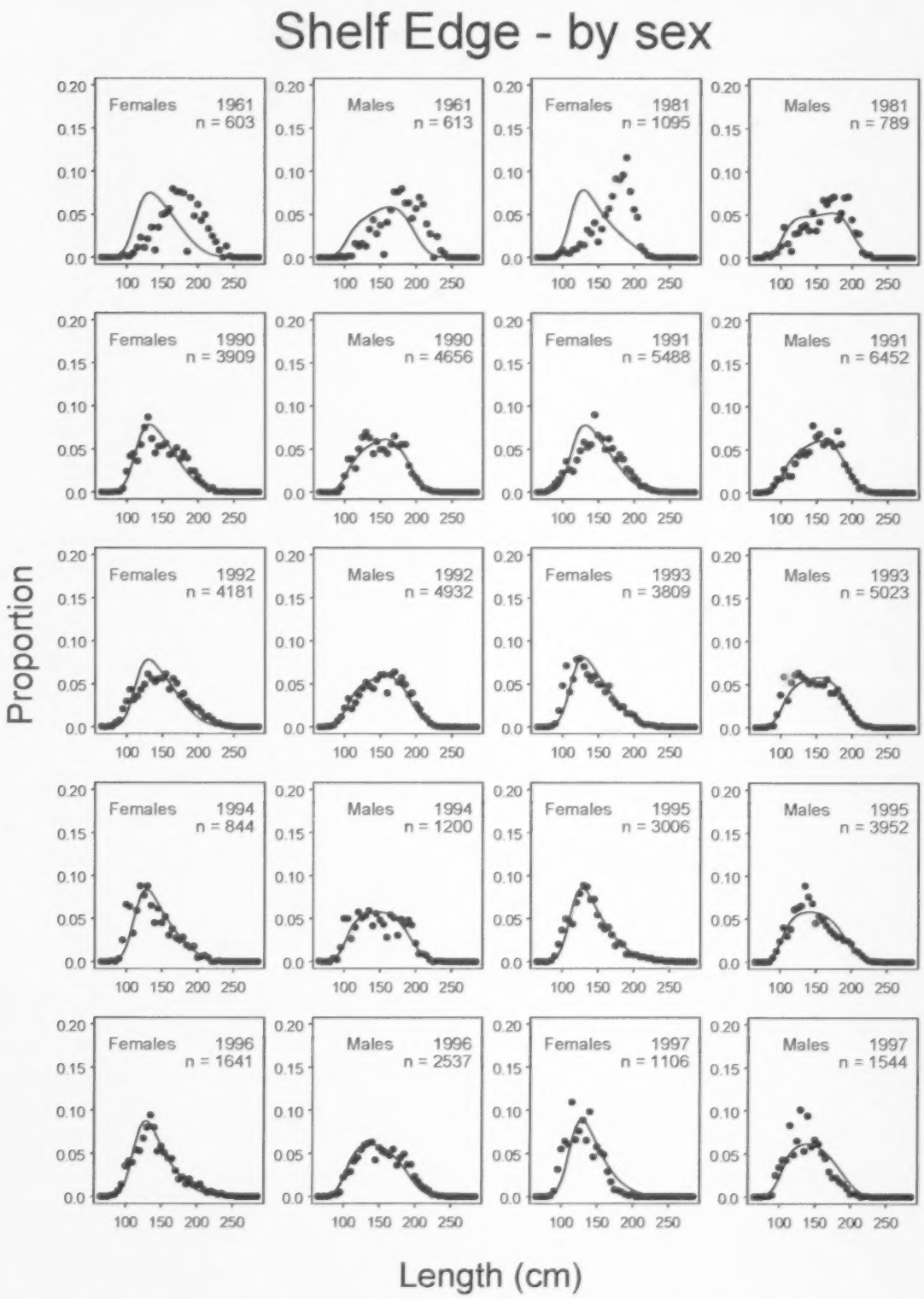


Figure 20.4. Observed (points) and fitted (lines) catch-at-length proportions by sex in the Shelf-Edge region. Line symbolism is the same as Figure 19.

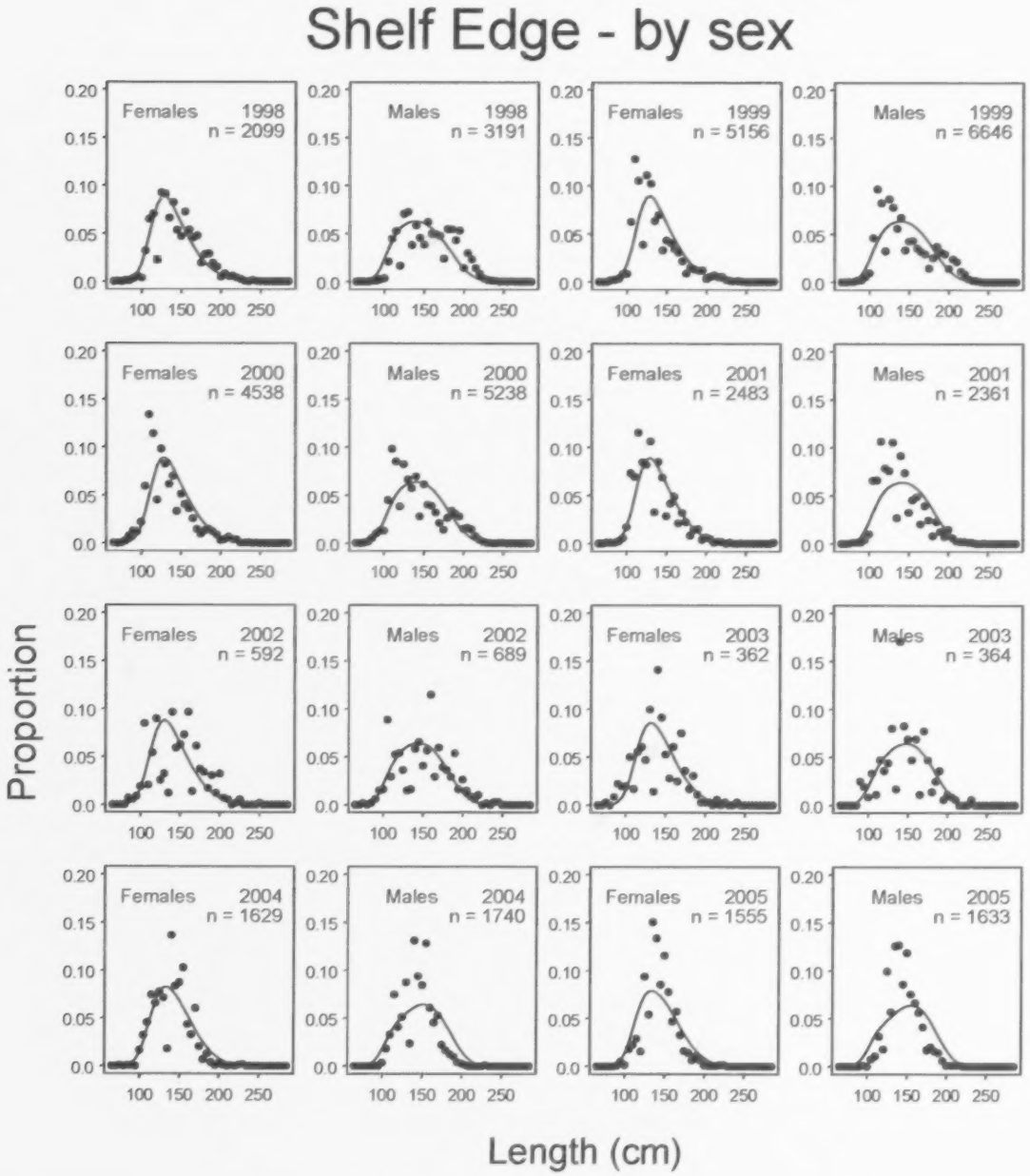


Figure 20.5. Observed (points) and fitted (lines) catch-at-length proportions, sexes combined in the Shelf-Edge region. Line symbolism is the same as Figure 19. All fits are virtually identical (continued below).

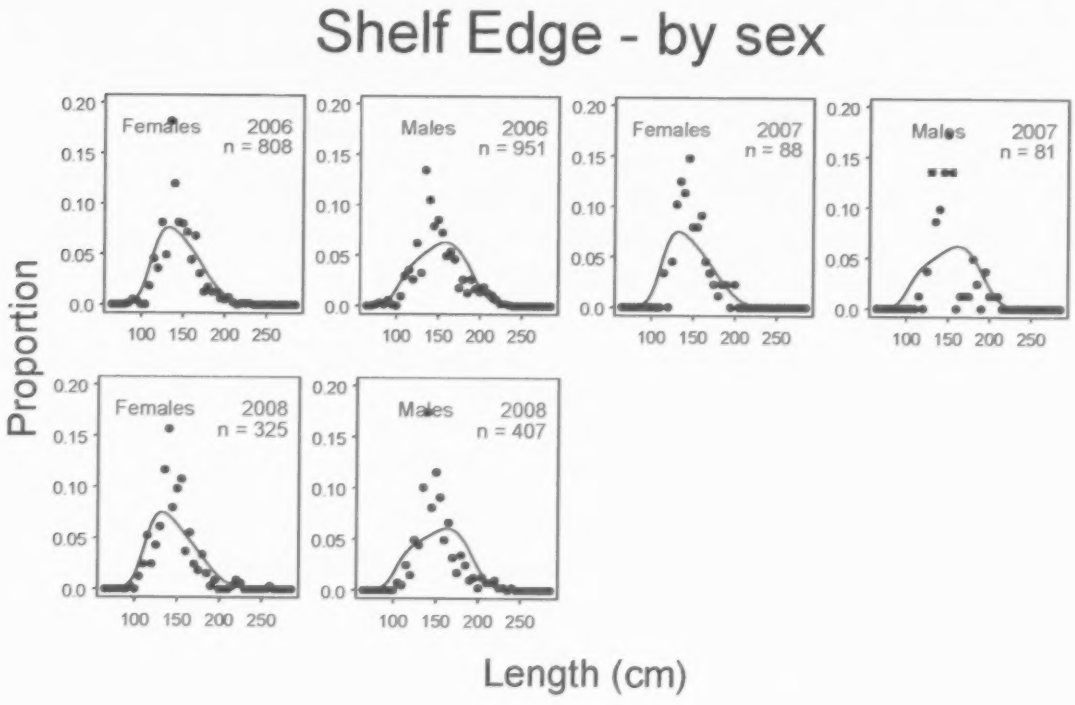


Figure 20.5. Continued.

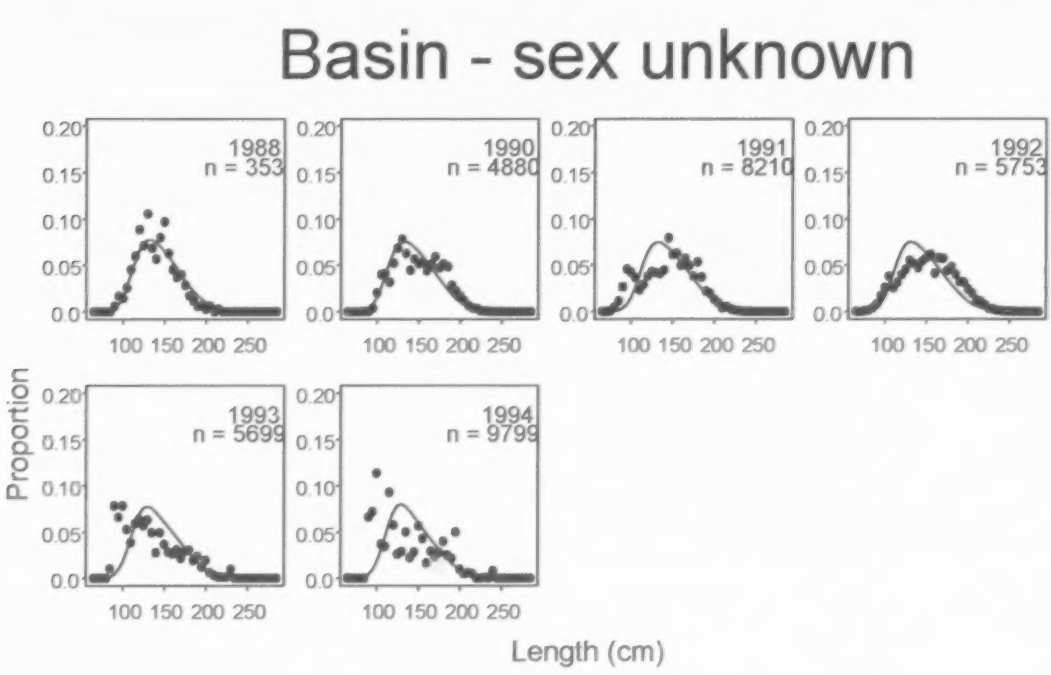


Figure 20.6. Observed (points) and fitted (lines) catch-at-length proportions, sexes unknown in the Basin region. Line symbolism is the same as Figure 19. All fits are virtually identical.

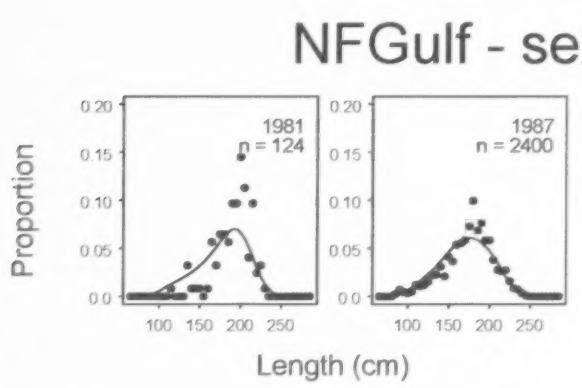


Figure 20.7. Observed (points) and fitted (lines) catch-at-length proportions, sexes unknown, in the NF-Gulf region. Line symbolism is the same as Figure 19. All fits are virtually identical.

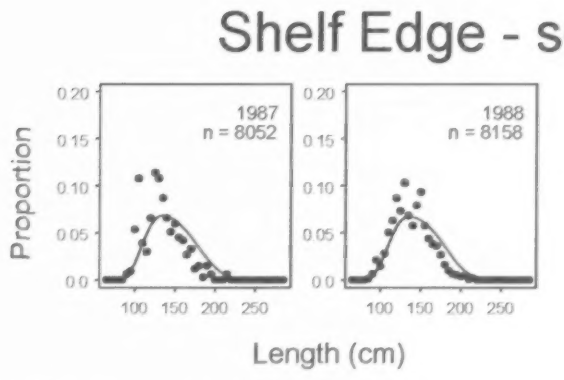


Figure 20.8. Observed (points) and fitted (lines) catch-at-length proportions, sexes combined in the Shelf-Edge region. Line symbolism is the same as Figure 19. All fits are virtually identical.

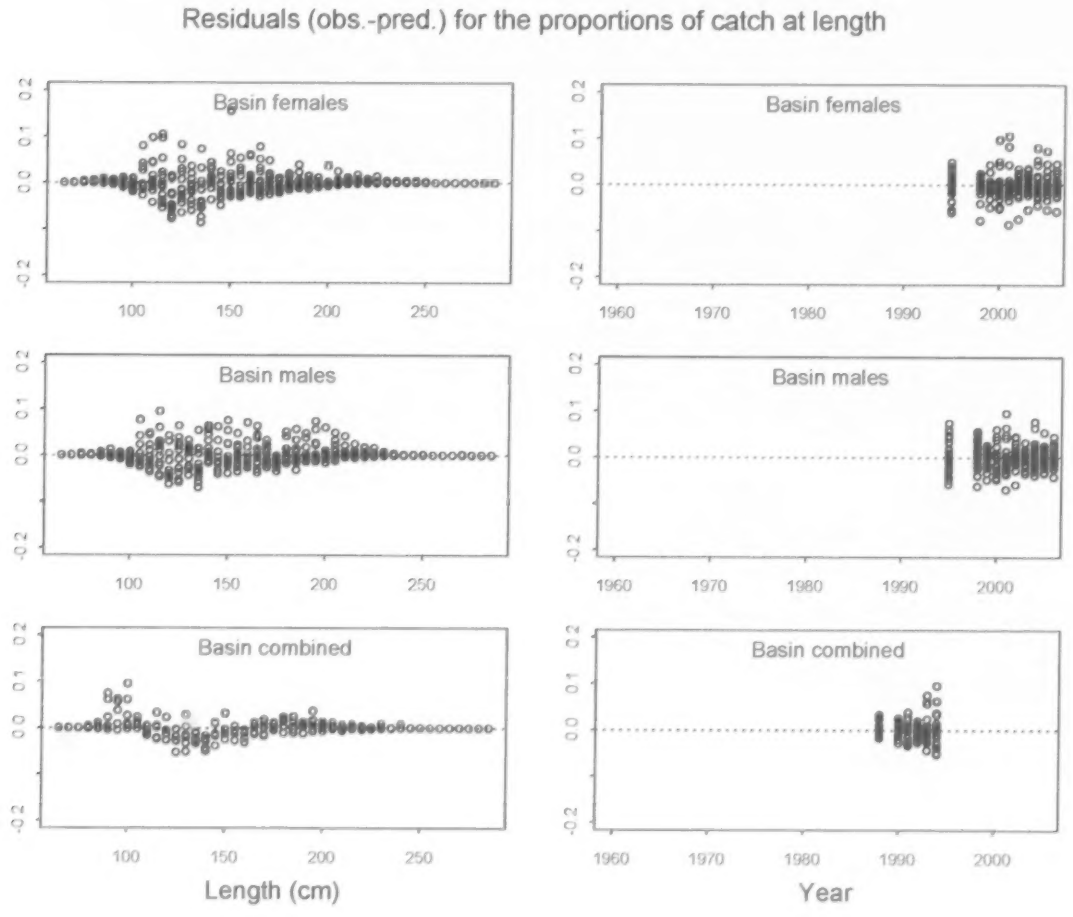


Figure 21.1. Raw residuals for fits to the catch-at-length data by length and by year for the Basin region obtained from Model 3.

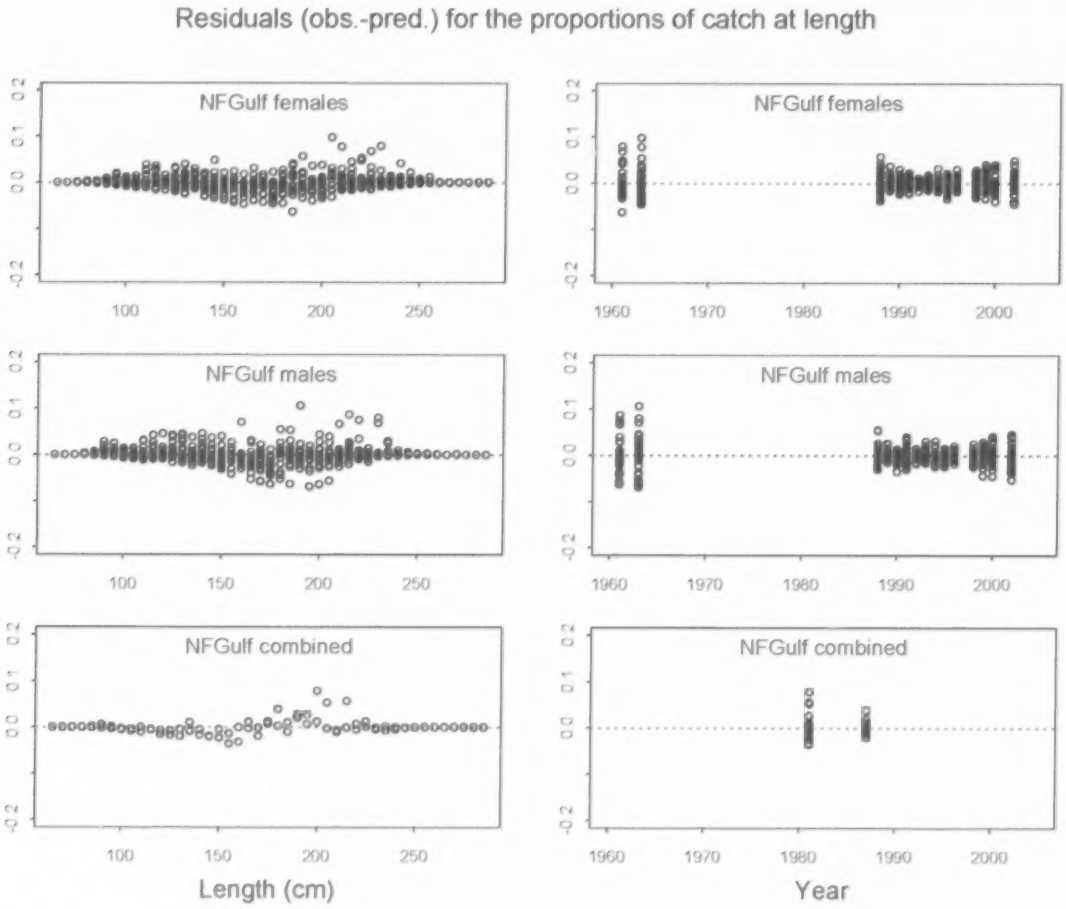


Figure 21.2. Raw residuals for fits to the catch-at-length data by length and by year for the NF-Gulf region obtained from Model 3.

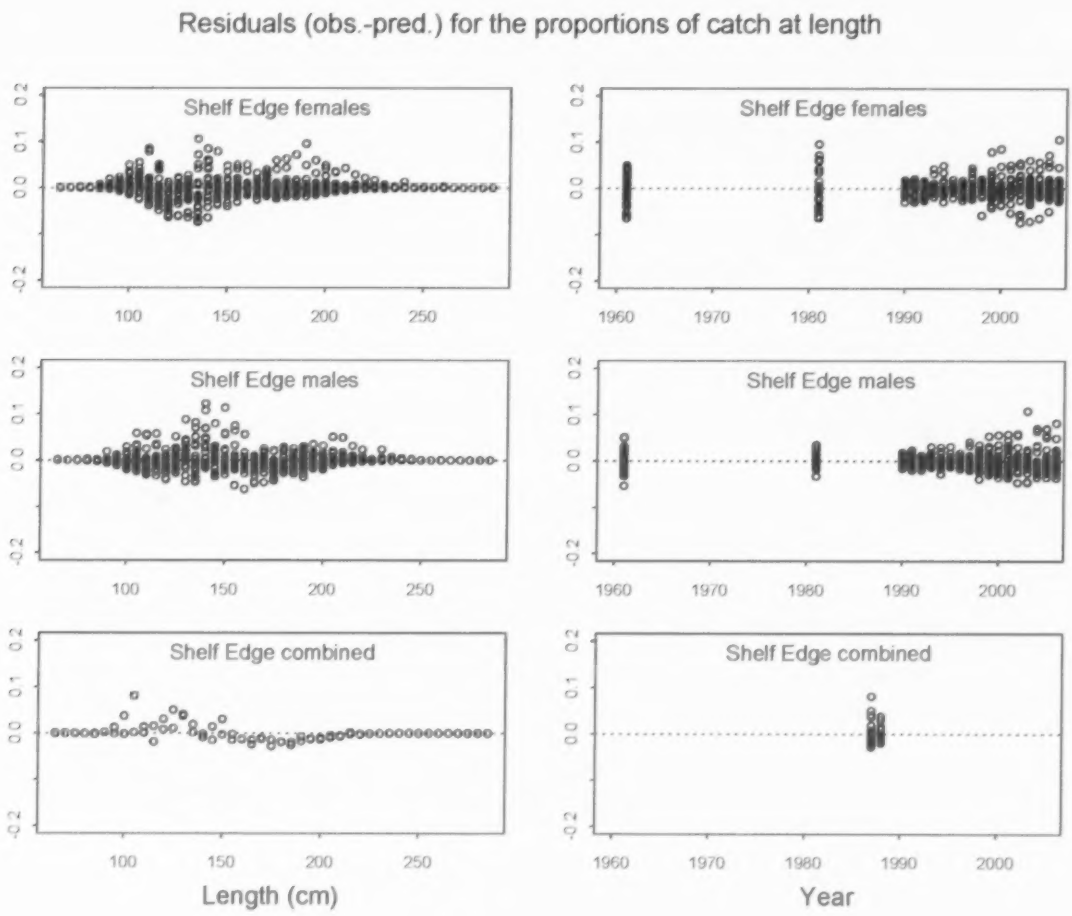


Figure 21.3. Raw residuals for fits to the catch-at-length data by length and by year for the Shelf-Edge region obtained from Model 3.

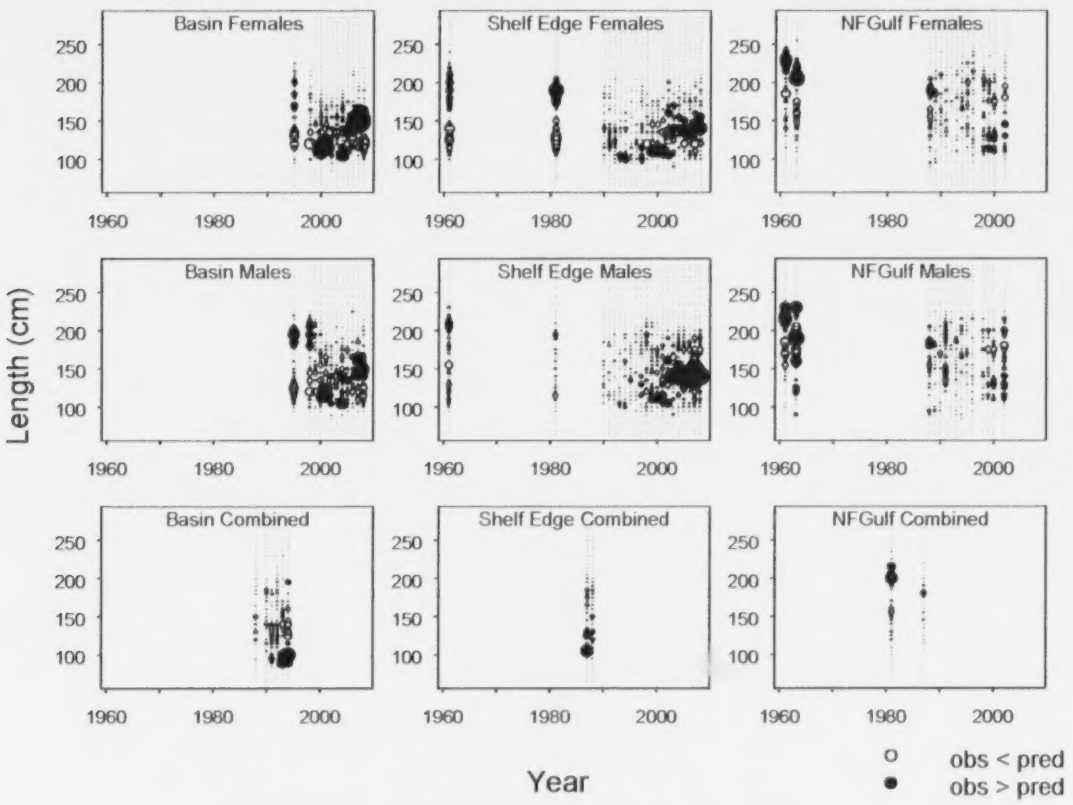


Figure 22. Raw residuals for fits to the catch-at-length data for the three regions obtained from Model 3.

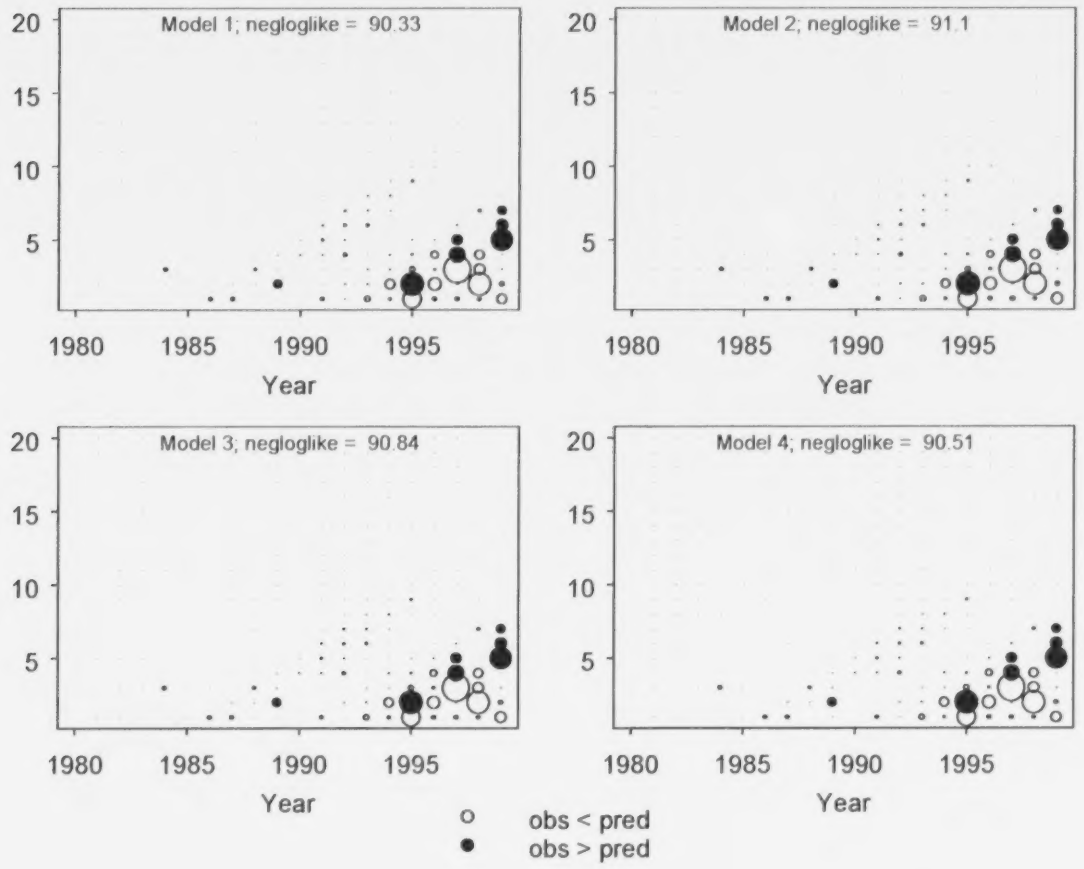


Figure 23. Residuals (observed tag recaptures - predicted tag recaptures) for the tagging component of the model. Points are proportional in size to the size of the residual (max. 12.5).

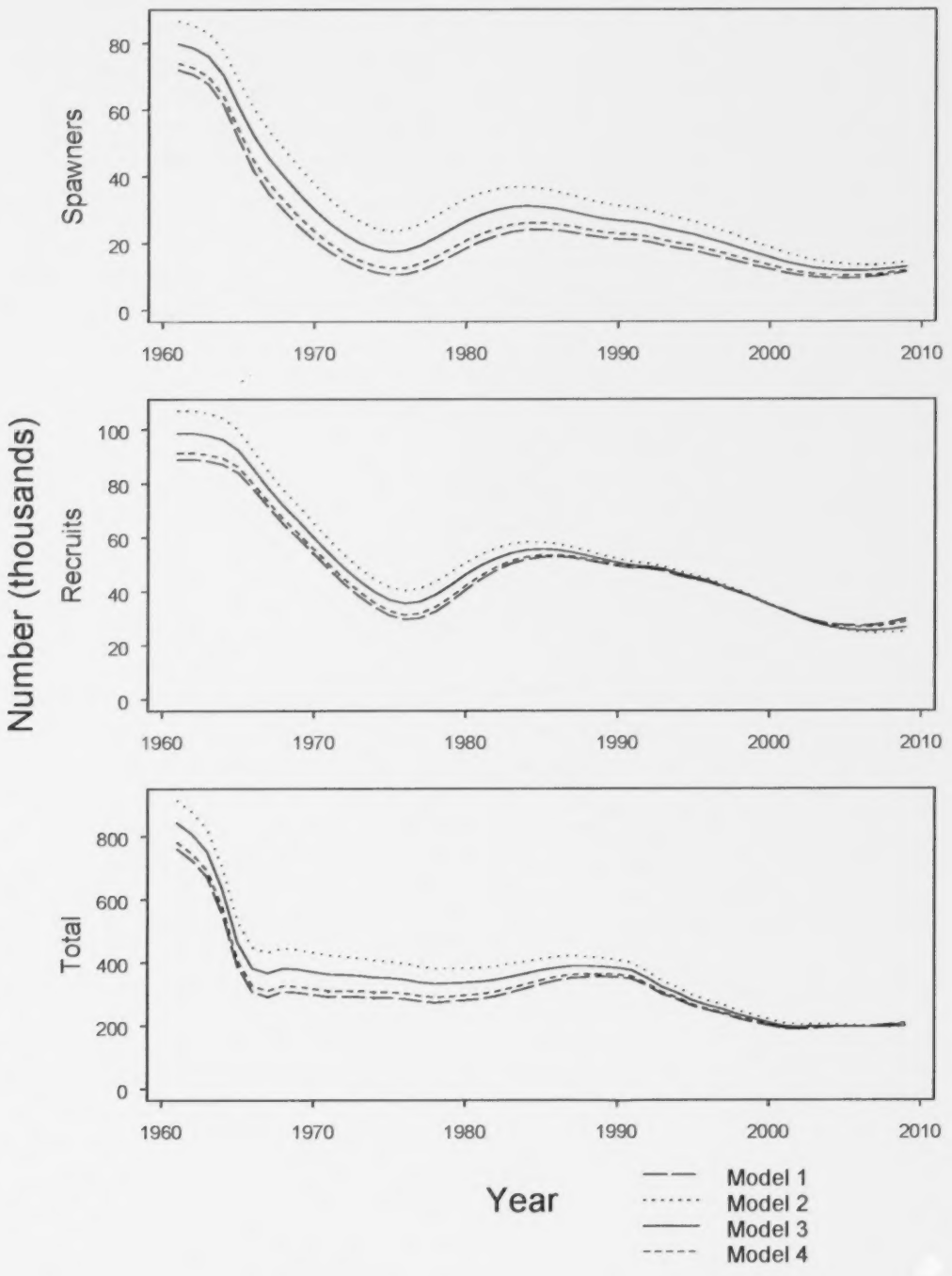


Figure 24. Comparison of the predicted time series for female spawner abundance, recruitment at age-1 and total number from each of the four models.

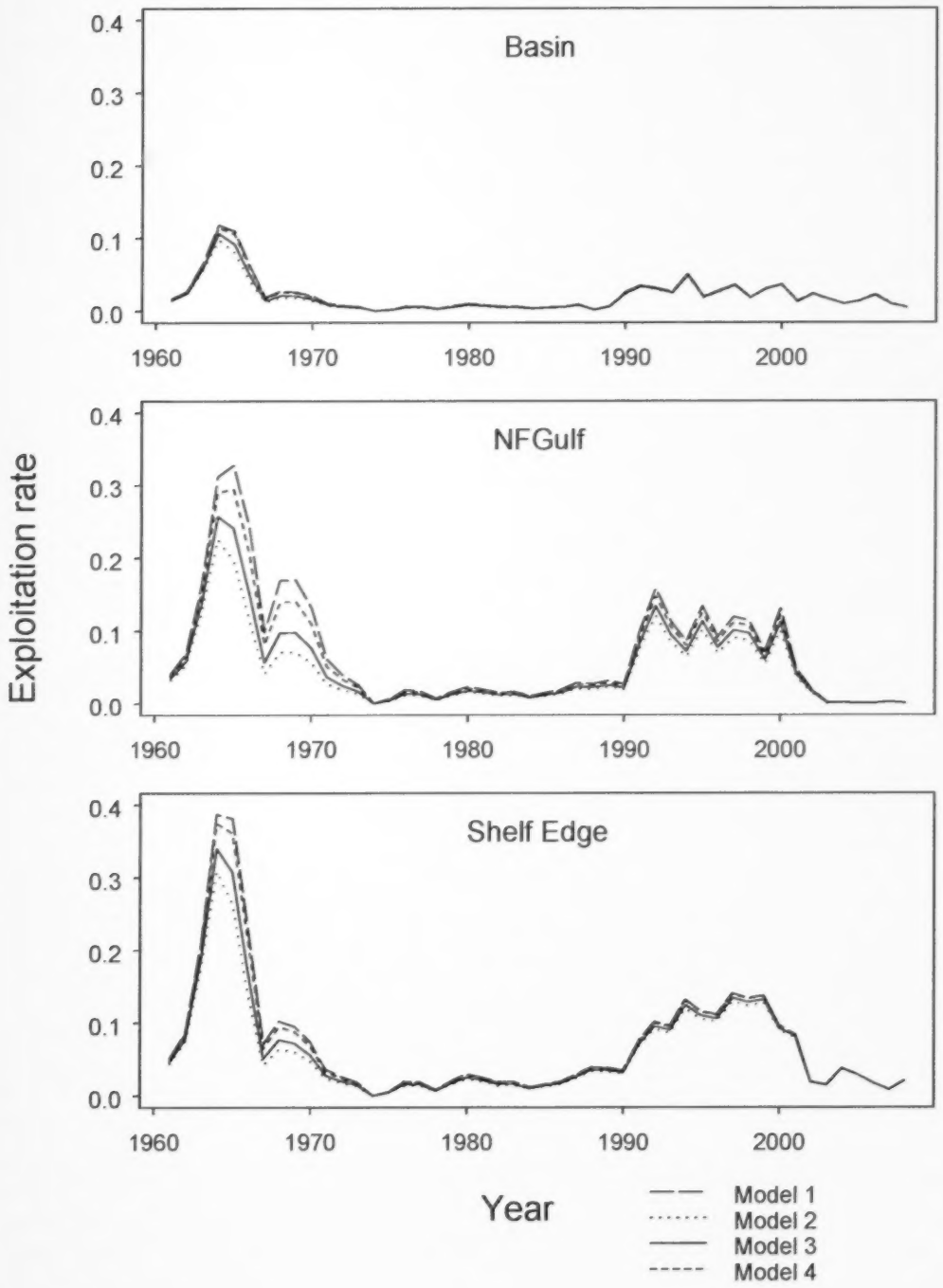


Figure 25. Comparison of the predicted time series of exploitation rates (proportion of the vulnerable biomass) from each of the four models. Line symbolism is the same as Figure 13.

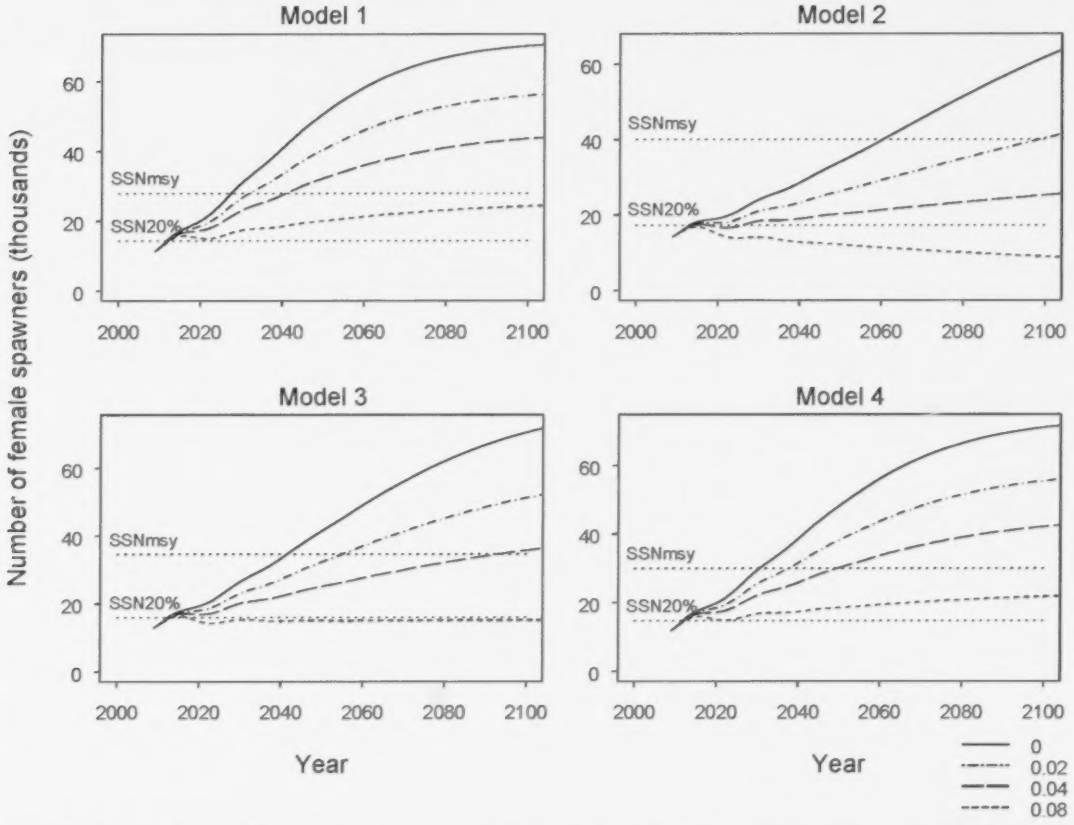


Figure 26. Comparison of the recovery targets and recovery trajectories obtained from each of the four models (see text for description) assuming four different exploitation rates (and the Shelf-Edge selectivity). Population projections begin in 2009 from the abundance by age and sex predicted by the model, and are projected deterministically using the life history parameters obtained from the model and the assumed exploitation rate. The Shelf-Edge selectivity is used in each case.